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The Remedial Action Assessment System
Automated Decision Support for the CERCLA RI/FS Process

David J. Crow

This technical report is submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in Public Health in the Department of Environmental Sciences and Engineering.

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Abstract

David J. Crow. The Remedial Action Assessment System--Automated Decision Support for the CERCLA RI/FS Process.

The Remedial Action Assessment System (RAAS), a computer-based decision support system currently under development at Battelle Pacific Northwest Laboratories, was presented with an emphasis on expanding the capabilities of the software. RAAS is being developed to provide the benefits of decision support software to Superfund decision makers. The first version of RAAS focuses on automating the process of screening remediation technologies for their applicability at a hazardous waste site. Four specific contributions to RAAS development were made: three remediation technologies to be included in the RAAS technology database were described; methods to include technology screening based on applicable or relevant and appropriate requirements (ARARs) were discussed; criteria to extend the RAAS technology screening procedure to include discrimination based on effectiveness and implementability were developed; and a procedure to validate RAAS output against the work of environment consultants was presented. When fully implemented, RAAS has the potential to both expedite and standardize the Superfund remedy selection process.

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Abbreviations

ARARs	Applicable and Relevant or Appropriate Requirements
ARARs Assist	ARARs Assistant
CAA	Clean Air Act
CELDS	Computerized Environmental Legislative Database System
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CFR	Code of Federal Regulations
CORA	Cost of Remedial Action System
CWA	Clean Water Act
EPA	Environmental Protection Agency
FFA	Federal Facility Agreement
FR	Federal Register
FS	Feasibility Study
FWQC	Federal Water Quality Criteria
GRA	General Response Action
IAG	Inter-agency Agreement
MCL	Maximum Contaminant Level
MEPAS	Multimedia Environmental Pollutant Assessment System
NAAQS	National Ambient Air Quality Standards
NCP	National Contingency Plan
NESHAPs	National Emissions Standards for Hazardous Air Pollutants
NPDES	National Pollution Discharge Elimination System
NPL	National Priority List
PA	Preliminary Assessment
PCB	Poly-chlorinated Bi-phenol
POHC	Primary Organic Hazardous Constituent
POTW	Publicly Owned Treatment Works
RAAS	Remedial Action Assessment System
RACER	Remedial Action Cost Estimating Routine
RCRA	Resource Conservation and Recovery Act
RI	Remedial Investigation
ROD	Record of Decision
S/S	Solidification/Stabilization
SARA	Superfund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
SI	Site Inspection
SITE	Superfund Innovative Technology Evaluation
TCE	Trichloroethylene
TSAR	Technology Selection of Alternative Remedies
TSCA	Toxic Substances Control Act
USC	United States Code
VOC	Volatile Organic Compound

I. Introduction

The Comprehensive Environmental Response Compensation and Liability Act (CERCLA) was passed in 1980 to force companies and governments to clean up uncontrolled hazardous waste sites to standards which are protective of human health and the environment.¹ Although the original law provided strong language to compel companies to remediate these sites, it provided little guidance on how the final clean up remedy for the site would be selected. Those who drafted the law had envisioned that negotiations between the regulatory agency and the site owner would result in a satisfactory remediation plan.

Unfortunately, the drafters did not foresee that tens of thousands of sites would be identified by 1985 nor did they envision the diversity of contaminant types and site conditions that would fall under the CERCLA umbrella. The National Contingency Plan (NCP) is the regulatory framework which codifies the CERCLA legislation.² The NCP was developed pursuant to CERCLA and provided basic guidance on the proper course of action once an uncontrolled hazardous waste site is discovered. Because the process of site characterization and remedy selection was inadequately defined in the original version of CERCLA, the Superfund Amendments and Reauthorization Act (SARA) of 1986 required that the NCP be revised. Section 121 of SARA directed that a comprehensive strategy for identification and selection of remedies be developed. The revised NCP, which incorporated the SARA requirements, was published as a final regulation in March, 1990.³

The database which the U.S. Environmental Protection Agency (EPA) uses to track the status of all potential and active Superfund sites contains about 30,000 entries. 1,211 of these sites are on the National Priorities List (NPL) and are actively being remediated.⁴ Because a huge number of sites must be investigated under the highly structured

¹42 USC 9625.

²40 CFR 300.

³55 FR 8666.

⁴56 FR 35840. The number of NPL sites is current as of 29 July 1991.

regulations of the NCP, the process of remedy selection is an obvious candidate for the use of computer-based decision support systems. These systems, often called expert systems, combine a rule-based decision structure with a domain-specific database in an attempt to automate the process used by experts to reach complicated decisions.

Purpose. This paper presents one such expert system currently under development to support the CERCLA remedy selection process. The Remedial Action Assessment System (RAAS) is being developed at Battelle Pacific Northwest Laboratories for use at Department of Energy facilities. It will also be available to other government agencies and will be available to private consultants who purchase a license from Battelle. At the time of this writing, RAAS is being fielded for its first operational tests.

RAAS focuses on automating the process of screening technologies for their applicability at a particular hazardous waste site. Depending on the contaminant and the medium in which the contaminant is bound, one or more treatment processes may be combined to develop a treatment scheme which can effectively clean up the site. The RAAS database contains over 90 different waste remediation technologies. Using a mass balance model to examine effectiveness and using inference rules to determine applicability, RAAS searches its database and develops a list of potential remediation scenarios for a site.

RAAS was conceived to provide the benefits of expert systems to Superfund decision makers. The benefits normally ascribed to expert systems are speed, comprehensiveness and an auditable decision trail. Because RAAS is currently under development, this paper pursues two goals. First, the paper will present work done to support development of RAAS. This work includes defining additional technologies for the RAAS database and detailing portions of the formal CERCLA decision process for inclusion in the RAAS inference mechanism. Second, the paper will propose a method to validate RAAS output against remedy selections made for existing Superfund sites. From these two elements, recommendations for improvements to the RAAS program are proposed.

The paper is divided into six sections. Section II provides background information on the CERCLA process, expert system software and RAAS itself. Section III describes three technology modules prepared for RAAS. Sections IV and V address two critical CERCLA considerations: 1) the legal requirements for site cleanups, often known as applicable or relevant and appropriate requirements or ARARs, and 2) the formal process for technology screening prescribed by CERCLA. Both sections propose decision rules for RAAS to implement these issues. Section VI presents the proposed validation method and Section VII presents recommendations for future refinements.

II. Background

A. CERCLA Process

The detailed CERCLA process begins with discovery of a contaminated waste site and concludes with declaration that the site has been cleaned up to the satisfaction of the appropriate regulatory officials. This process is codified in the NCP and documented in numerous EPA publications, for example (EPA, 1988e). For this discussion, the process can be represented by the seven-step methodology shown in Figure 1. The diagram is further divided into what can be considered the study phase and the action phase.

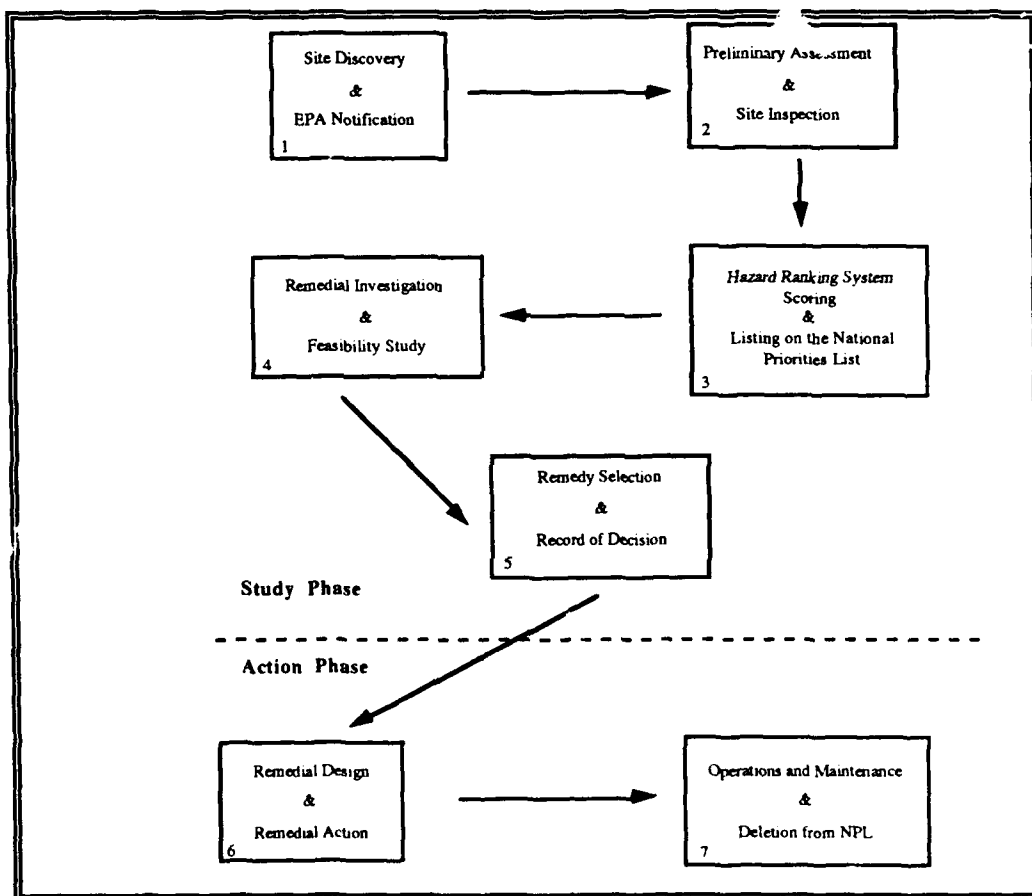


Figure 1. Seven Step CERCLA Process.

In the study phase, after initial discovery and notification, the site is evaluated on an initial basis in the preliminary assessment (PA) and, if warranted, the site inspection (SI).

At each stage, a determination is made if the site should be further considered. If sufficient

threat is discovered in the PA/SI, the site is listed on the National Priorities List (NPL). All NPL sites are scheduled for a remedial investigation (RI) to elaborate on the findings in the SI. Closely coupled to the RI is the feasibility study (FS) which is used to screen and ultimately select the remedy that is implemented in the action phase of the process.

Figure 2 depicts the RI/FS process as described in EPA regulations. Note that the diagram shows how the RI and the FS are integrally linked throughout the process. The goal of the RI/FS is to select the remedial action plan to be endorsed in the Record of Decision (ROD) and implemented in the remedial action phase.

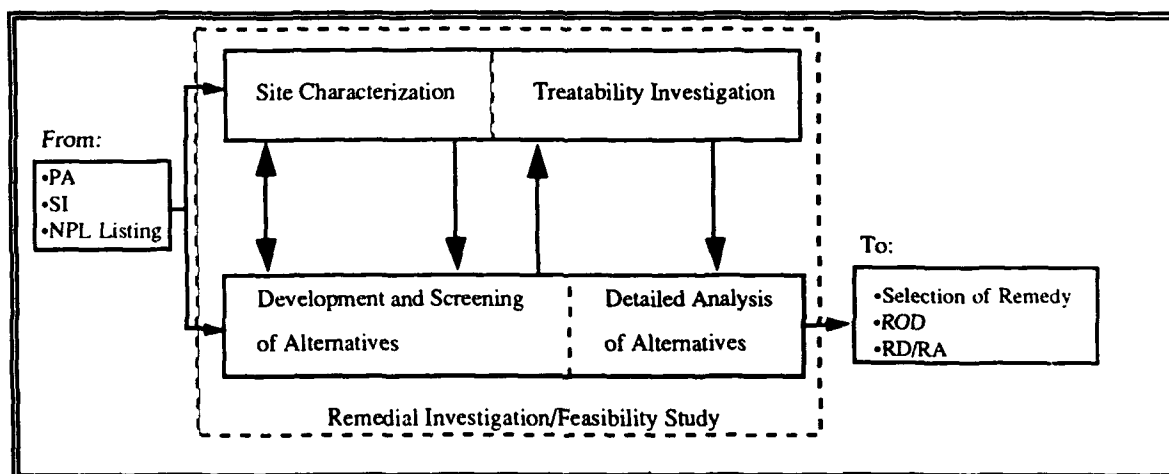


Figure 2. Remedial Investigation/Feasibility Study Process.

Because the primary objective of the Superfund program is to protect human health and the environment, activities which expedite the study phase must be exploited. EPA has taken severe criticism for the length of time and cost required to complete the study phase.⁵ In response, EPA and others have conducted several studies and published additional guidance in an effort to expedite the process (e.g. Clean Sites, 1990). Unfortunately, the net result of the criticism, study and guidance has been little improvement in the overall time required to reach the ROD.

One of the most cited reasons for the excessive time required to complete the study phase is the time required for regulatory and citizen review at each stage of the process.

⁵See for example, Washington Post, 19 June 1991, page A1, A14.

The underlying problem with this issue has been understaffed agencies unable to meet realistic review schedules. In order to alleviate this pressure, agencies are focusing on providing adequate trained staff to perform the reviews in reasonable time. At present, none of the players in Superfund is considering changing the time allowed for review.

Another commonly cited reason for the delay is the time required to adequately investigate the site and document the nature and extent of contamination. This the heart of the RI process. In order to expedite this phase, EPA recommends collecting and analyzing a minimum number of samples at each stage of the study. Of course, identifying a minimum number of samples is an artistic process rather than a scientific one. An iterative process has been adapted from geotechnical engineering and is now used by some consulting firms (Myers, 1989). By collecting only the necessary data for each step in the decision, this "observational approach" can avoid excessive time and cost for analytical data collection.

Another cumbersome process often cited as time consuming in the RI/FS process is the screen and selection of the final remedy (Clean Sites, 1990). Because many potential technological options may be applicable, each one must be considered in a cursory manner during screening. While many environmental professionals have developed their own rules-of-thumb to perform this exercise, no comprehensive EPA guidance on the subject has been developed. Thus, the remedy selection process is conducted on a case-by-case basis and rarely yields consistent results.

RAAS attempts to automate this screening process. By modeling the remediation technologies in mass balance terms and describing the critical FS steps in decision logic, RAAS develops a list of potentially applicable technologies from the broad range available.

Finally, the determination of the "applicable or relevant and appropriate requirements", the identification of the laws that determine the level of clean up that must be made at the site, has also been a troublesome part of the RI/FS process. The ARARs are identified in the remedial investigation and finalized when the detailed remedial alternatives

are determined. Section IV below will discuss the details of the ARARs identification process and suggest ways that RAAS can capture its critical features.

Once a set of potential remediation alternatives is identified, the final step in the feasibility study is the detailed analysis of the alternatives (see Figure 2). SARA provided a detailed list of nine evaluation criteria to be used to compare the alternatives. Figure 3 lists these nine criteria. Under the revised NCP, the detailed analysis of alternatives must objectively discuss each of the alternatives based on each criteria. The analysis is done to determine the relative performance of each alternative and to identify the major trade-offs among them (EPA, 1990c).

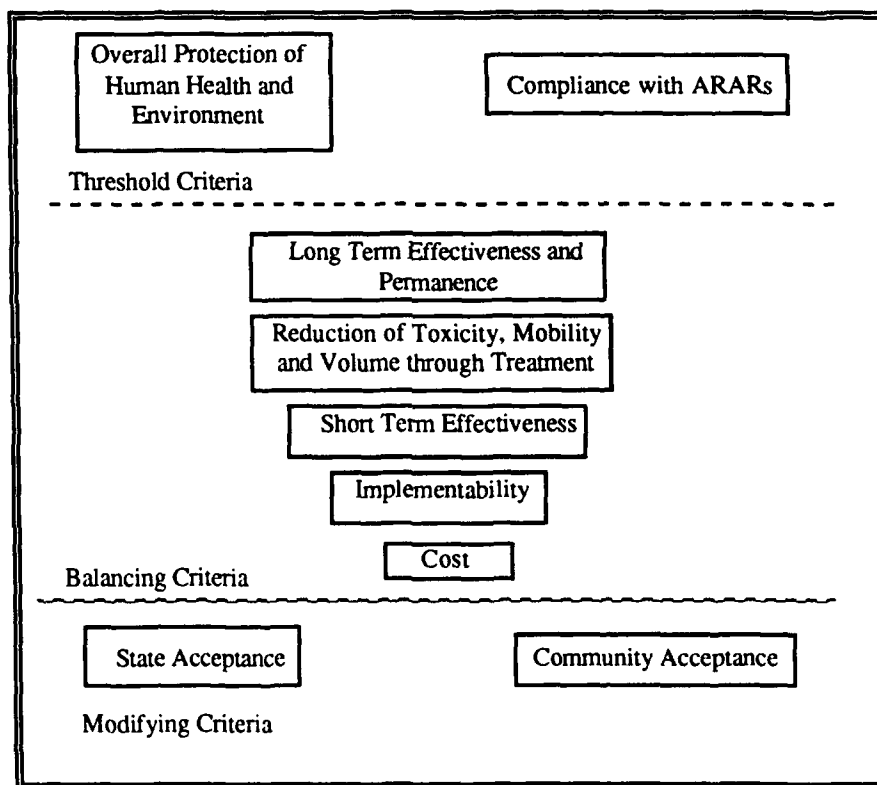


Figure 3. Criteria for Detail Analysis of Alternatives.

The NCP distinguishes the detailed analysis of the alternatives from the final remedy selection. In the NCP, the final remedy selection is based upon the detailed analysis of the alternatives. The decision maker must use the nine criteria as they are grouped in the three headings, threshold, balancing and modifying, shown in Figure 3.

No remedy failing the two threshold criteria may be considered in the final selection. The balancing criteria are used to trade off between the alternatives and to determine the alternative which is most "cost effective and utilizes permanent solutions and alternate treatment technologies or resource recovery technologies to the maximum extent practicable" (EPA, 1990c). Finally, comments from the state and community may be used to modify the alternative selected or choose another alternative.

The culmination of the study phase is the signing of the Record of Decision (ROD). By signing the ROD, the site owner and the various regulatory agencies agree to implement the selected remedy. With the ROD in place, the action phase can be implemented. While the NCP provides the EPA a course of action to remediate a life threatening site prior to the ROD (the removal action in 40 CFR 415), all sites selected for the NPL must be studied via an RI/FS before a ROD is signed and the final remedial action is implemented.

This paper discusses RAAS as a method to expedite and standardize the study phase of the CERCLA process. It should be noted that to date, EPA has signed over 700 RODS (EPA, 1991a). Thus, many sites now have activities underway in the action phase (Figure 1) of the remediation process. A majority of these sites are under design or construction. Relatively few have operational clean-ups in progress. Because EPA has only completed remediation at approximately 60 sites, emphasis is still required to provide the means to cut the time required to select the remedy and sign the ROD. In the future, as more of the sites move into the action phase, EPA will certainly be challenged to expedite the action phase as well.

B. Expert System Software

1. Expert System Paradigm

Expert systems are "computer programs that perform sophisticated tasks once thought possible only for human experts." (Benfer, 1991) Expert systems are distinguished from other types of computer software that assist in decision making, like

spreadsheets or statistical packages, by their use of programming methods such as symbolic representation of knowledge and heuristic reasoning (Hushon, 1990; Benfer, 1991). Today, the term expert system defines a specific type of software that represents the knowledge of an expert in a narrow domain and provides that knowledge to less sophisticated users. These programs are also often called knowledge-based systems.

Expert systems are a product of artificial intelligence (AI) research. When computers were first developed, some envisioned systems that would be able to reason like the human mind. While AI research has continued with more realistic projects such as speech and visual recognition, expert systems development spun off as its own field. Expert system developers create practical applications using AI tools (Holtzman, 1989). The first well-documented expert system was called MYCIN. The MYCIN system was developed to aid doctors in identifying antibiotic therapies for infectious blood diseases. MYCIN captures the diagnostic heuristics of doctors in a program which elicits conditions about the patient and suggests potential remedies. Another early expert system, called PROSPECTOR, assisted geophysicists in exploring for mineral deposits. Like MYCIN, PROSPECTOR encoded the decision rules used by experts and allowed rapid, consistent application of the rules in various settings.

Today, knowledge-based expert systems are ubiquitous. In a 1986 book, Waterman identified 181 different systems (Waterman, 1986). Hushon found 69 systems fielded or under development in the environmental field in a 1990 review (Hushon, 1990). While environmental expert systems are relatively new, knowledge-based systems are especially prevalent in the financial world doing everything from stock trading to screening loan applications. With the development of more powerful computers, the term knowledge-based system is evolving to include powerful systems which integrate visual recognition and domain expert knowledge. As an example, researchers at Carnegie-Mellon have fielded a prototype autonomous vehicle which can "see" and interpret roadway signs and markings (Mark, 1991).

One can imagine that expert systems are indicated in many situations. The list of criteria in Table 1 suggests six basic criteria which might be used to decide if an expert system is warranted. Others have developed an elaborate questionnaire and decision framework for those contemplating a major investment in expert system software (Laufmann, 1990). As was mentioned above, the process of remedy selection under CERCLA meets several of the criteria which suggest expert systems.

Table 1. Characteristics that Suggest the Use of Expert Systems.

•Situations Occur Often	•Uncertainty Involved
•Situations are Complex	•Situations are Dynamic
•Knowledge of Expert Required	•Need for Consistent Response

With a basic definition of an expert system in mind, Figure 4 shows the four major components of an expert system. This basic configuration can be implemented on a wide range of computer platforms. Originally, expert systems were implemented on main frame computer in a research setting. Increased processing capabilities of mini computers, work stations and personal computers has allowed expert systems to run effectively on these smaller systems. Indeed, the growth of the use of expert systems in many different fields has paralleled the growth in power of smaller computer systems. Today, rather than individually designed and coded programs, many expert systems are developed in what are known as "expert system shells." Expert system shells facilitate development of the four components of the expert system without requiring the developer to be fully versed in the details of artificial intelligence programming. The RAND Corporation published a methodology for those interested in matching the right expert system development tool to their needs (Rothenberg, 1987).

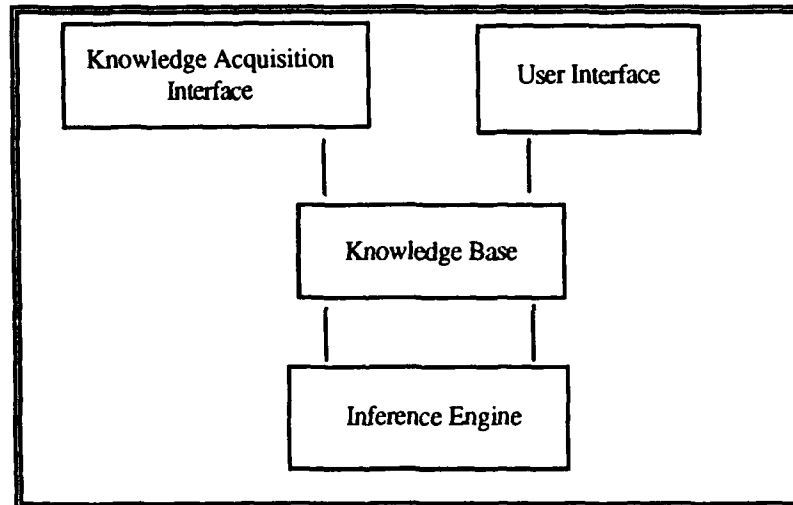


Figure 4. Components of An Expert System.

The user interface, as with many other software applications, is the place where input/output operations are conducted. In more advanced expert systems, the user interface is effective in eliciting the necessary information from the user and in presenting the expert advice in the proper context. An additional critical feature of the user interface is the ability to document the reasoning used by the program in reaching its conclusions. Fully developed systems can provide the user the option of performing sensitivity analysis or simulations (Benfer, 1991). Graphical representation can be an effective means of performing many of these functions at the user interface.

The knowledge-acquisition interface provides the link between the expert and the knowledge base. On most systems, this interface is a human one. A "knowledge engineer" trained in elicitation techniques and familiar with expert systems technology aids the system developer by encoding the expert knowledge in a format that is readable by the programmer. Expert system shells now offer on-line versions of this service. These systems present the expert with options to represent his knowledge and facilitate its structuring. Advanced systems allow graphical representation of the knowledge base and an ability to test the execution of the program based on sample questions. These systems also monitor the syntax of the input and track the number of rules and variables (Benfer, 1991). Automated knowledge acquisition interfaces are best suited for systems that can be

fully expressed in terms of a deductive reasoning "if-then" format. Systems that integrate numerical functions will require programming efforts beyond the scope of the shell.

The heart of the expert system is the knowledge base and the inference engine. The knowledge base is like other databases in that it stores information about a specific domain. In addition, the knowledge base represents domain information with if-then rules and other methods such as "frames." Frames represent associations among concepts as nodes with arcs between them (Hushon, 1990). These deductive and symbolic structures allow for a much richer representation of the problem. The knowledge base can represent more than a static database because of its link to the inference engine. Through inference, implicit conclusions can be drawn that extend the database beyond its structured representation of information.

The inference engine provides the mechanism to query the knowledge base and develop additional conclusions. It provides a means of interpreting the symbolisms in the knowledge base and deducing unstated results. Often the reasoning utilizes mathematical formulas to develop additional information from the input data and infer subsequent results. In addition, inference engines can accommodate the concepts of probability or rules-of-thumb to capture the subjective nature of many decisions. The inference engine is most directly linked to the field of artificial intelligence and to formal studies of reasoning.

The development of expert system environments has exploded in the last five years. With this growth of software and consultants, those wishing to employ expert systems no longer need the computer programming skills necessary to construct a system from scratch. The flood of tools and salesmen however, does necessitate that new users understand the applicability, strengths and weaknesses of expert systems.

2. Expert System Advantages and Disadvantages

The advantages attributed to expert systems follow logically from the characteristics listed in Table 1 which indicate situations when an expert system might be warranted.

Specific advantages are dependent on the environment in which the system is implemented

(e.g. business, industry or government settings). The advantages summarized in Table 2 are generally applicable in any situation (CSS, 1989; Waterman, 1986). The specific application will dictate the magnitude of these advantages.

Table 2. Advantages of Expert Systems.

- | |
|---|
| <ul style="list-style-type: none">•Tackle Complexity<ul style="list-style-type: none">- Sail the "Sea of Information"- Create a "Human Window"•Present Consistent, Reliable Information<ul style="list-style-type: none">- Preserve Corporate or Institutional Knowledge- Pool Resources of Multiple Experts- Train Novice Employees•Provide Cheap, Available Advice<ul style="list-style-type: none">- Time Savings/Cost Reduction- Free Experts from Routine Tasks- Share Scarce Resources |
|---|

By providing a detailed representation of a decision or control structure, an expert system allows a manageable analysis of a problem. Within a given domain, decision makers are often confronted with "sea of information" (CSS, 1989) which might be applicable to a decision. By structuring this information in a knowledge base, greater amounts of this information can be brought to bear on the final choice. In complex control systems such as power plants, expert systems can clearly present complicated, conflicting information to operators and suggest solutions that otherwise might be overlooked.

For decisions that must be made repeatedly, the one-time cost of encoding the problem in an expert system can create a source of cheap, available advice. The expert system is most often sold on this criterion. The benefits in time savings and cost reduction are often argued to exceed the cost of system development. More broadly, an expert system can make advice from multiple experts available. By developing the knowledge base from interviews with several domain experts more robust advice may be created. Additionally, the expert system can free scarce experts from routine decisions and allow them to focus on unique and challenging problems. Finally, along similar lines, by

implementing the expert system on multiple workstations, an operation can effectively share limited expert resources.

Well designed and programmed expert systems present consistent and reliable information to users. Expert systems can provide managers some consistency between field personnel. By approaching each problem from the same broad perspective, the resultant decision is likely to be grounded on similar principles. In addition, a well-documented expert system can provide an excellent training tool. Users can input a variety of circumstances and learn the process followed by the system. Most expert systems create reports that also foster consistency and learning. The expert system is not likely to fall pray to illness or absent-mindedness which adversely affect human experts. Lastly, they can preserve corporate or scientific knowledge which might be lost when the expert retires. Benfer calls expert systems "inherently cumulative." (VanHorn, 1986; Benfer, 1991)

An understanding of the disadvantages of expert systems is more important for new users of experts systems. Otherwise, considerable time and expense can be invested in unwarranted software which is rarely used. Table 3 notes some of the often cited problems of expert systems. Some of the disadvantages are simply the opposite of the advantages listed in Table 2. These problems are likely to be found in poorly planned systems which were not adequately justified.

Table 3. Problems with Expert Systems.

•Provide Wrong Answers	•Contain Hidden Rules
•Use Too Many Assumptions	•Advice Interpreted Incorrectly

Perhaps the most significant problem with an expert system is that it can provide wrong answers. By linking together disparate aspects of the knowledge base, the output may actually be harmful. A medical expert system that recommended 20 aspirin in a case with complicated symptoms was cited as an example of a truly dangerous wrong answer (CSS, 1989). The authors provide several reasons why expert systems can deliver

incorrect information. First, the knowledge base may itself be wrong, either by factual or structural means. If the knowledge is correct, problems may still arise because of faulty rules, improper interpretation of synonyms supplied by the user or an inability to interpret complex input (CSS, 1989). Finally, the knowledge base may have been created from interviews with poorly qualified "experts" or developed by untrained "knowledge engineers." (Van Horn, 1986)

Hidden rules represent another serious concern for expert system users. Hidden rules can be described as rules that discriminate between different answers in ways that are unknown to the user. An excellent example which demonstrates the impact of a hidden rule might be found in an expert system which screens loan applications. The rule might state:

If the subjects address is in Chicago,
And the subject's age is less than 25,
And the subject is non-caucasian,
Then the credit rating is poor. (CSS, 1989)

In this rule, if the non-caucasian statement is not clearly documented, it discriminates in subtle but powerful way. More disconcerting examples might arise when results of linking several of these nested if statements yields the discriminatory information. These types of rules could easily be extended to bias against treatment methods or technological choices in other applications.

When the knowledge base encodes extensive assumptions, the expert system output can also be problematic. By chaining together an extended list of assumptions, the system can generate absurd or potentially dangerous advice. These assumptions can also be harmful when they encode values that are not universally accepted in the community of users. Medical recommendations that violate a users religious or ethical beliefs may be technically correct but will alienate the user (CSS, 1989).

A final serious problem arises in the use of expert systems when the user misinterprets the recommendations of the system. Surveys have found unsophisticated

users are inclined to be very trusting of computer output. In both time-critical and highly technical fields, this blind faith in a system can have catastrophic results. The aphorism "a little knowledge can be a dangerous thing..." aptly encompasses the concern of many expert system critics (CSS, 1989).

In an article examining research directions for expert systems, Wesley captures both the potential advantages and disadvantages of expert systems with the "equation" (Wensley, 1989).

$\text{Expert System} + \text{Novice} = \text{Expert}$

This "equation" clearly shows the advantages of availability and ease of use attributed to expert systems. Closer inspection, however, points to the pitfalls of ready acceptance of this expression. The novice must both provide the right input to the system and accurately interpret the results. Systems that claim these issues are not a concern almost assuredly are not warranted except perhaps as training tools or as archives of knowledge.

3. Issues in Expert System Development

Proper protocol for developing expert system is widely documented (Benfer, 1991; Waterman, 1986). Originally, expert systems were developed along the lines of traditional software development ("life-cycle development") which involves extensive documentation and analysis prior to any actual programming. As shells have become available, the expert system development process has evolved as a different form of programming. This process, called rapid prototyping, involves first developing a basic version of the program which shows how the final system might look and act but has a very simple knowledge base and inference structure (Waterman, 1986). With the help of the expert and the knowledge engineer, the knowledge base is then expanded. This process mirrors the human learning process and allows the representation of the decision to grow with the capabilities of the system. This process continues until the system reflects the skill of the human expert. Four key issues which must be addressed in this development process are discussed below.

Knowledge Acquisition. A well defined strategy for knowledge acquisition is essential for a complete representation of the problem and a fully operational software tool. Techniques of elicitation useful in traditional decision analysis (Holtzman, 1989) and social science research (Benfer, 1991) are commonly prescribed for knowledge acquisition. The determination must be made whether one or several experts will be consulted and how differences in their opinions will be reconciled. Another critical decision is whether to use experts from "inside" or "outside" a field of expertise or both. The necessary methodology for acquisition may drive the choice of the shell used for the program (Rothenberg, 1987).

Knowledge Representation. As was mentioned briefly above, different formalisms are available to represent the knowledge base (e.g. trees or "frames"). Trees are favored in systems which consider a single issue at a time whereas frames are useful where multiple combinations of information must be considered simultaneously (Benfer, 1991). More broadly, a work notes "it may be that the act of representing knowledge and inference as explicit rules will help to uncover assumptions and bias in the minds of those on whom the program is modeled." (CSS, 1989) Knowledge representation must be a central focus in the early stages of program development. The more robust the structure, the more likely the program will evolve and remain useful as the domain of expertise expands.

A final issue concerning knowledge representation is the need to explicitly acknowledge that political, social and epistemological viewpoints are critical in most decisions. (Kjaergaard, 1989). Without an analysis of the stakeholders in the decision, the system may be discredited by those who are damaged by its recommendations. These issues are often so fundamentally held by domain experts that careful use of independent observers may be necessary to avoid these pitfalls (Benfer, 1991). The setting in which the system will be used, either public or private, also affects the representation of knowledge. The public sector has political, economic and environmental factors unique to it which can affect the way information is shared (Jenkins, 1989).

Verification and Validation. The process of validating expert system software is difficult because of the system's ability to draw conclusions beyond the explicitly stated data. Thus, systematic validation is difficult (Benfer,1991). Because validation is such a critical issue, Section VI of the paper is devoted to this issue.

Handling Uncertainty. Uncertainty management is the heart of an effective expert system. In order to capture the knowledge and skill of a human expert, the software must account for the human ability to consider the likelihood of events based on evidence that itself is inherently uncertain. Table 4 lists both the typical causes of uncertainty encountered in expert systems and theoretical and pragmatic methodologies employed to address uncertainty. It serves as an outline for the following discussion of uncertainty management.

Table 4. Uncertainty Management.

<u>Sources of Uncertainty</u>	
- Unreliable Information/Data	- Imprecise Descriptive Language
- Inference with Incomplete Information	- Poor Integration of Knowledge from Multiple Experts
<u>Methods of Uncertainty Management</u>	
•Complete Theories	•Expert System Techniques
- Probability Theory	- Certainty Factors
- Demster-Shafer Theory	- Subjective Bayesian Method
- Possibility Theory	- Theory of Endorsement

Fundamental uncertainty stems from two sources: unreliable data and uncertain knowledge (CSS, 1989). Data collected from observation or instrumentation that are used as input to an expert system can be wrong, contaminated or incomplete. This inherent uncertainty forces the user to understand its source and provide the expert system a way of incorporating measurable variability in the data. Understanding the weaknesses of measurement methods is directly linked to understanding and representing the uncertainty in the underlying theory or knowledge. When an expert system attempts to emulate a

human expert in an area where concepts are poorly defined, the resultant advice must be qualified by this underlying lack understanding.

A second source of uncertainty can be attributed to the imprecision with which our language is able to represent complex ideas. Expert systems often attempt to accommodate input in "natural language." Thus, a broad range of synonyms and viewpoints must be contained in the database. When the system is forced to proceed based on a tenuous or erroneous assumption about the input, the resultant advice will be similarly affected.

Beyond imprecision in language, operational expert systems must function with data that does not match any definition in the database. These incomplete problem definitions add further imprecision to the information on which an expert system will ultimately make a recommendation. These vacancies can occur both in the data and in the representation of the problem.

Finally, in systems which acquire knowledge from multiple experts who disagree, the representation of this disagreement leads to unreliable output. In order to press forward, system developers represent a "consensus" viewpoint which results in often subtle biases (Ng, 1990). This representation ignores the even more subtle issue of the relative level of expertise among domain experts.

Formal representations of uncertainty are fundamental to science and mathematics. They were developed long before the advent of computers or expert systems. Table 4 indicates three different theoretical models used to represent uncertainty. Each was developed to serve a particular aspect of uncertainty management. When applied in expert systems, each serves to combine uncertain existing knowledge and predict uncertain future events. Ng and Abramson call this process "belief propagation." (Ng, 1990)

Probability theory is by far the oldest and most widely used method for representing uncertainty. The basic principles of probability theory are at the heart of modern statistical analysis. Probability theory uses Bayes' Theorem to obtain the probability that a hypothesis is true given the observation of some evidence that has a

known probability of being true. Observing the assumptions of mutually exclusive and exhaustive hypotheses, Bayes' Theorem can be used to combine available information to decrease the uncertainty of a hypothesis. Of course, the underlying premise necessary to apply probability theory is that all of the necessary conditional probabilities can be determined--no small task. Often, the assumption of the independence of the probabilities of separate pieces of evidence for a given hypothesis is made in order to limit the number of conditional probabilities that must be determined. Even with these additional simplifications, a significant information gathering burden remains.

Dempster-Shafer theory is motivated by the difficulty in probability theory in expressing ignorance. The theory is both mathematically and symbolically complex and has not been implemented in operational expert systems.

Possibility theory, which is based on the concept of fuzzy sets, has been implemented. Possibility theory replaces the binary logic in probability theory with system that allows "shades of gray" to be expressed. Membership in a fuzzy set is not bound to the yes or no criteria of probability theory sets. In addition, there is no restriction on the sum of the possibilities of an outcome. In probability theory, the sum of the probabilities of an outcome must equal 1. Fuzzy logic allows a range of logic properties and allows belief propagation to be formally expressed and coded. Those who question the utility of possibility theory note that because a possibility set is defined subjectively, no additional accuracy is introduced into the definition. Due to its potential, fuzzy set theory is an area of extensive research (Ng, 1990).

Because of the difficulty in fully implementing probability theory and the complexity of the other theoretical approaches mentioned above, several less mathematically rigorous approaches have been developed. (See bottom of Table 4.) Certainty factors and the subjective Bayesian method are quantitative whereas endorsement provides a qualitative representation of information.

Certainty factors were developed in conjunction with MYCIN because the developers felt that inadequate medical information would be available to allow implementation of probability theory. Certainty factors are the most commonly used method of uncertainty management in expert systems fielded today. A certainty factor can range between -1 and +1 with -1 representing a bit of evidence confirming that a hypothesis is false and +1 representing evidence confirming that a hypothesis is true. Formal rules for combining certainty factors have been developed and implemented in software. The key assumption in the use of certainty factors is the assumption that all hypotheses are mutually independent. Because of the weakness in this assumption, theoreticians continue to narrow the range of applicability of certainty factors.

The subjective Bayesian method relies on the concept of likelihood ratios. The likelihood ratio is defined as ratio of the probability that the evidence is true given that the hypothesis is true ($p(E|H)$) to the probability that the evidence is true given that the hypothesis is false ($p(E|\bar{H})$) which can be thought of as the odds that $p(E|H)$ is true. This method has several key assumptions such as conditional independence of evidence under both a hypothesis and its negation. These demands are rarely met and systems that overlook these restrictions have been shown to perform poorly.

Endorsement theory attempts to represent the reasons for believing a hypothesis. This qualitative theory is beyond the scope of this report but is mentioned here for completeness (Ng, 1990).

The preceding discussion of uncertainty management is based on an understanding of probability theory and was derived from sources who endorse probability theory as the most rigorous approach to uncertainty management. Unfortunately, probability theory is impossible to implement fully. Thus, users of expert systems must look at the simpler models for uncertainty management and understand their inherent assumptions prior to utilizing them.

Because the uncertainty in a complex decision structure is multi-faceted and ubiquitous, no model can claim to represent it all. The uncertainty management issue must be an explicit component of the basic design of an expert system and must constantly be reviewed and documented throughout testing and implementation.

4. Beyond Expert Systems

No single method has been proposed for representing and programming expert systems for decision support. In fact, the growing availability of expert system shells is causing the number of development tools to proliferate. In an interesting attempt to provide a unifying paradigm, Holtzman proposed an expert system based on the formal concepts of decision analysis (Holtzman, 1989).

Holtzman focuses on the importance of the distinction between the decision maker and the decision analyst. He expresses concern that in current expert system application, this distinction is confused and blurred. When in the system development, the domain experts assume the role of the decision maker, they impart their preferences and information on the decision maker in very subtle ways. They may not ask the sort of basic questions that help to create an accurate, flexible representation of the decision structure.

To combat this bias, Holtzman recommends a decision analysis approach to problem formulation. He suggests the use of influence diagrams to formally outline all aspects of the decision problem. Through this rigorous analysis, the problem can be structured to explicitly recognize the decision maker's attitudes toward risk and preferences. With the formal structure laid out in an influence diagram, the required subjective probability information can be elicited from either domain experts or the decision maker and integrated into the influence diagram. *The resultant assemblage can then be queried to determine the appropriate recommendation for action.* In his book, Holtzman diagrams the set of computer based programs that must be associated to fully automate the process he advocates. He bolsters his position by describing a medical diagnosis system which he developed using his paradigm.

Holtzman suggests three main advantages of his "intelligent decision systems" over traditional expert systems. First, he states that the intelligent decision system, because of its clearly defined decision structure, is more effective in focusing the knowledge acquisition process. Second, because uncertainty is explicitly confronted using decision analysis methodology, the knowledge representation and uncertainty management schemes are more effective. And third, because his model specifically acknowledges preferences in the decision framework, it has a greater normative power. In other words, an intelligent decision system can more effectively determine which alternative among those considered is better. He argues that the decision analysis methods used to define the preferences and circumstances of a particular decision augment the domain expertise of a traditional expert system and create a more powerful tool.

Of course, as was discussed above, the use of formal probability concepts comes at a significant cost. Tools of elicitation must be employed to objectively determine decision maker preferences and probability distributions associated with the knowledge base. Numerous conditional probability statements must be elicited to ensure that the chance nodes in the influence diagram are properly described.

The methodology presented by Holtzman is certainly not appropriate for all expert system applications. It does, however, offer a rigorous scheme which can be employed in high risk situations where full representation of all aspects of the decision are important. Because it provides a formal treatment of probability and it attempts to explicitly state the portions of the decision which are influenced by decision maker preferences, it has the potential to be withstand a more thorough validation.

Having introduced CERCLA and the concepts of expert systems, the following section describes the Remedial Action Assessment System (RAAS). The discussion ties RAAS to the CERCLA process and examines its function as an expert system.

C. RAAS

1. Objective

Broadly, the objective of RAAS is to automate the CERCLA FS process. To achieve this goal, RAAS will ultimately be integrated with other expert systems (see discussion below). More specifically, RAAS's first objective is to automate the technology screening phase of the FS process. Referring to Figure 2, RAAS will provide the development and screening of alternatives based on a site characterization. The RAAS output will focus and facilitate the detailed analysis of alternatives. Successful use of RAAS should expedite signing of the Record of Decision and start of remedial action at the site.

In its initial phase, RAAS will provide the user a list of potential "treatment trains" for a contaminated hazardous waste site. A "treatment train" is defined as a set of unit remediation processes arranged in such a way that their implementation will lead to complete site clean up (e.g. a treatment train for a groundwater remediation might consist of a pump-and-treat treatment technology train). RAAS first identifies technologies that will effectively mitigate site risks and then arranges them in a sequence that will meet the overall objectives for site cleanup. Both the individual technologies and the resultant process are evaluated to ensure that they are viable with respect to basic technological constraints. In its current phase, RAAS will provide a comprehensive list of potential trains. All reasonable sets of alternatives will be submitted to the user for further review. Subsequent versions will include more discriminatory criteria that will allow a ranking of the potential alternatives.

The first phase of RAAS has several potential benefits. Several of the benefits are commonly attributed to expert systems. They include: decreasing the time and cost necessary to develop and screen alternatives and documenting the process used to reach the decision. In addition, RAAS can ensure that all potential technologies receive an unbiased consideration. This is especially important for new and innovative technologies that are

required to be considered under SARA but are unfamiliar to most practicing environmental professionals. Finally, RAAS provides a consistent vehicle for performing the screening. Once the regulatory community accepts the method used by RAAS, it may facilitate the acceptance of remedial action plans.

RAAS is not the first attempt to use a computer based expert system to automate remedy selection in the RI/FS process. Two other systems are documented in the literature (Hushon, 1990). The Cost of Remedial Action (CORA) model was developed by EPA and CH2M Hill primarily to assist the EPA in developing order of magnitude cost estimates for site cleanups. The output of the model is used to better budget for future Superfund expenditures. In order to budget for a clean up however, the developers found it necessary to at least guess at what type of technology would be employed at the site. Thus, as a front end to the cost estimating model, they built the "Technology Screening System." (Chenu, 1990) A similar system was developed by Roy F Weston and EPA (Hushon, 1990). The "Technology Selection of Alternative Remedies" (TSAR) was a prototype system which identified potential technologies and recommended additional input information that must be collected from field studies to verify the potential of the technology in the feasibility study. (Greathouse, 1989; Hushon, 1987)

Both CORA and TSAR used the traditional expert system approach to suggest remediation technologies. Their knowledge bases have IF...THEN... statements that suggest remediation technologies based on user answers to questions. In CORA, the questions are primarily true/false statements about the contamination and the site. The level and extent of contamination are not well qualified in the input. As a result, the output of the technology screening phase of CORA is very general and of limited value beyond scoping cost estimates. TSAR also focuses at the level of individual technologies and is primarily useful in identifying necessary field and laboratory investigations. While both systems are effective for their narrowly defined functions, they help to highlight the need for RAAS and its particular strengths.

As will be detailed below, the particular innovation most significant in the first phase of RAAS is its ability to model the effectiveness of remediation technologies. By representing each remediation technology as a unit process and describing its effect on the contaminant and media in a mass balance model, RAAS expands the potential site conditions which can be evaluated beyond those of the rule-based schemes in CORA and TSAR. RAAS can consider more technologies, more contaminants and a wider range contaminant matrix than the other models. By modeling the physical processes of remediation in addition to the procedural aspects of the CERCLA process, a more realistic simulation of the actual decision process is achieved.

2. Implementation Approach

This section describes the basic method RAAS uses to reach its objective. It relates the workings of the software in a graphic manner and explains the nature of the user interface. Depiction of an example "run" will help to reinforce these descriptions.

RAAS is developed using the object-oriented software development model (Bohn, 1991). In object-oriented programming, a decision problem is described in units that are natural to the process (i.e. as objects). Each object has an identity described with data or equations. The entire problem is thus defined as a set of objects that are linked together. By passing messages among the objects, the program can represent the decision process as time progresses. The critical concepts which make object-oriented analysis effective in describing the remedy selection process are that objects may be arranged hierarchically and inherit information from their parent object. In addition, specific instances of an object can be created during program execution to depict the results of different processes (e.g. instances that show the effects of different clean up technologies on a given waste matrix). Objects allow modularity in development and facilitate integration of knowledge from separate experts to emulate the real process--the CERCLA FS process.

Figure 5 shows the basic object-oriented structure used by RAAS to depict the CERCLA technology screening process (Bohn, 1991). The "cell" object contains the

physical description of the media and the contaminant in that media. It interacts with the "user interface" object to collect site information. The user interface also supplies information to the "planner" and "preprocessor" objects in order to control the selection of the technologies. The "planner" object represents the professional conducting the RI/FS. The "planner" coordinates and tracks the screening of technologies that will effectively clean up the site depicted in the "cell" object according to the general response action (GRA) defined by the user.

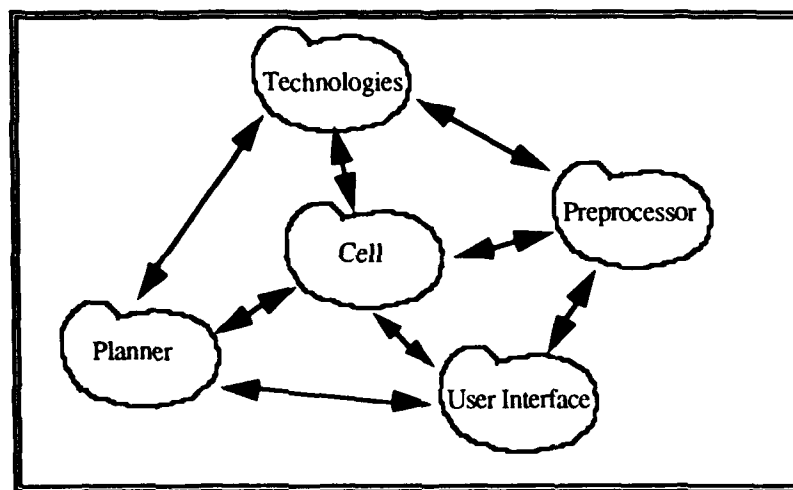


Figure 5. RAAS Object-Oriented Structure.

The GRA is a critical concept in the CERCLA process (EPA, 1988e). GRAs are general treatment approaches. For example, for a petroleum-contaminated groundwater, two typical general response actions might be applied. First, a collect--treat--dispose scenario might be employed such as a pump-and-treat activated carbon system. Second, an in-situ biological treatment approach might be implemented. GRAs are taken as user input or can be applied from system defaults. The "preprocessor" object facilitates the application of technologies which are unique to a particular GRA element (e.g. pumping is used as the collection component of the GRA). In concert with the preprocessor, the planner develops a sequence of technologies that solves the entire treatment objective consistent with each GRA sub-objective (Bohn, 1991).

The heart of the technology screening phase of RAAS is the "technology" object. Once the planner has an accurate representation of the existing conditions and has the user's objectives for clean up in the form of a GRA, it systematically queries technologies to develop viable treatment trains. The RAAS methodology uses two distinct processes to accomplish this task (Pennock, 1991).

The first task is to determine the applicability of a particular technology. This is shown in Figure 6 (Pennock, 1991). The technology object, which contains a series of enabling and disabling conditions, is queried relative to the site conditions. Second, the regulatory object is queried to determine if the technology is applicable in the given site conditions. The inference object facilitates this rule-based analysis by accepting knowledge, performing the inference and passing back the answer to the question. The net result of this sub-system is to determine in a qualitative manner if a technology is applicable.

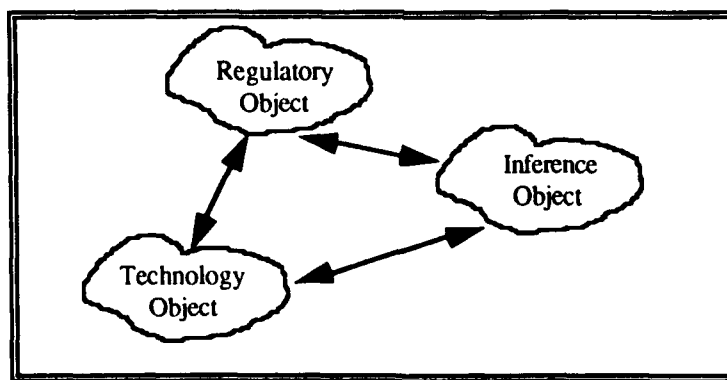


Figure 6. RAAS Qualitative Evaluation for Applicability

The second task is to determine the effectiveness of a given technology in meeting the clean up objective. Each technology is represented by a set of mass balance equations which model before and after conditions at the site when a technology is applied (see section III below). The model of each technology is a coarse numerical approximation which facilitates screening. Figure 7 shows how the technology object interacts with other objects to screen for effectiveness (Pennock, 1991). The contaminant, medium and reaction objects are knowledge bases which contain data about different chemical and

physical properties which might be encountered in a treatment process. The site object is a temporary instance of the cell object which shows how the site is altered after one or a series of technologies has been applied. The site object tracks all of the critical parameters so that the "planner" can determine if the technology is effective.

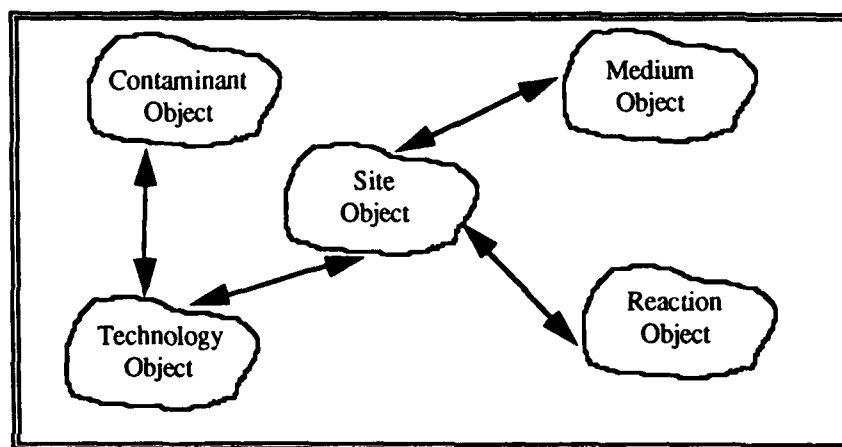


Figure 7. RAAS Qualitative Evaluation for Effectiveness.

As an example of the RAAS methodology, consider again the petroleum-contaminated soil. In the initial interaction with the user, the system would query for the principle contaminants (e.g. benzene or toluene) and the concentration of these contaminants based on field tests. Additional physical parameters such as soil type and hydraulic conductivity would also be elicited from the user. Next the GRA would be determined. For simplicity, assume that the user required that an in-situ bioremediation scenario be implemented.

In-situ bioremediation requires the ability to place biological agents into the soil and to provide them nutrients. The GRA might thus be described by two sub-components: injection and bioremediation. See Figure 8 for a graphic a representation of the process. In this scenario, the planner would first query the technology object database to select an injection technology and then query to select a bioremediation technology.

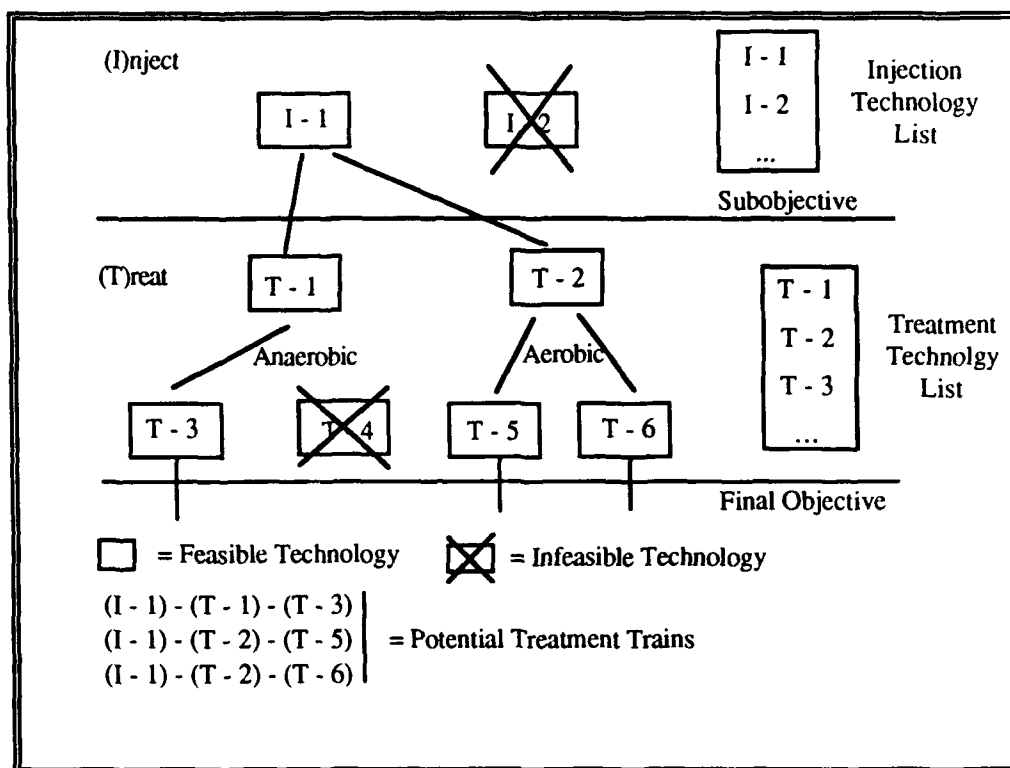


Figure 8. RAAS Technology Screening Process.

Consider the bioremediation technology screening. First assume that two potential technologies are available: aerobic and anaerobic bioremediation. When the planner invoked the aerobic treatment, the applicability determination would be made first. Then if found applicable, the technology object would run the mass balance model for aerobic bioremediation and compare the residuals to the constraints of the program and those supplied by the user. If found effective, the planner would link the technology with a successful injection technology to create a complete treatment train. The resultant treatment train and any others that are screened as both applicable and effective would be submitted to the user for further evaluation. Figure 8 shows a result which includes three potential treatment trains. Each uses the same injection technique but two use aerobic and one uses anaerobic biodegradation. The user could then interact with RAAS to examine the decision process and find out more information about the potential treatment methods.

3. RAAS as an Expert System

Strengths. RAAS clearly employs the four basic components of an expert system shown in Figure 4. The user interface communicates through interactive screens which elicit site data and a GRA from the user and return potential treatment trains and supporting information. The inference engine is utilized by the technology objects to evaluate for applicability and by the planner to determine the overall effectiveness of a potential treatment train. Knowledge acquisition is accomplished by augmenting several of the different objects which contain data. This distribution of the knowledge base is one of the primary justifications for the object-oriented programming method used.

The critical programmatic innovation in RAAS is the distribution of the inferencing and numerical calculations among the different technology objects (Pennock, 1991). This distribution will allow incorporation of additional objects which allow RAAS to further emulate the FS process. It will also facilitate RAAS's interaction with other software systems which might provide unique input to the model of the FS process.

Weaknesses. The current version of RAAS also possesses several weaknesses. They include: knowledge representation and uncertainty management. These weaknesses will be addressed in subsequent versions of the program but deserve mention here so that future work is focused on them.

While RAAS's object-oriented framework for alternative screening is functional, the framework for a RAAS method which performs a detailed analysis of alternatives is not clearly defined. The realm in which the final remedy selection is made is highly political and an adequate representation of this process will be elusive (Kjaergaard, 1989). In addition, RAAS plans to integrate with three other systems which will provide data on cost, risk and regulatory compliance essential for the ultimate remedy selection.

The Multimedia Environmental Pollutant Assessment System (MEPAS) system, also developed by Battelle, is an information management system which attempts to automate the risk assessment element of the RI/FS process (Droppo, 1990). The decision

structure to allow passing parameters to and from MEPAS must be designed to integrate risk-related information at the appropriate steps in RAAS execution. The Remedial Action Cost Estimating Routine (RACER) system⁶, under development by the Air Force, will provide detailed, site-specific cost estimates for remedial actions. As with MEPAS the RACER program must be queried at the appropriate times and with the appropriate parameters to emulate advanced screening and the detailed analysis of the alternatives. The ARARs ASSIST system, which will provide detailed information on ARARs compliance, is discussed in section IV below. Other systems, yet undeveloped, may be required to give RAAS sufficient capability to accurately screen the treatment trains and then analyze the best ones based on the nine criteria set out in CERCLA section 121 by SARA and codified in the NCP. See Table 3 above.

RAAS must also further address the issue of uncertainty management. Under the first phase, the program does not provide the capability to represent the variability in either the site data or the output of the numerical mass balance models of the remediation technologies. While these shortfalls are not fatal to RAAS's first phase objective of providing a list of potential treatment technologies, in order for future versions of RAAS to have credibility differentiating between proposed treatment technology trains uncertainty management must be carefully implemented in the program.

4. Summary/Need for Further Development

RAAS can be seen to have two objectives. The first, technology screening, will be operational with the first phase of the software. The second, advanced screening and remedy selection, can only be achieved in subsequent versions. As was previously stated, the objectives of this paper are to assist with the implementation of phase one of RAAS and to provide information which will help to focus the work in subsequent phases.

⁶The RACER program is being developed by the U.S. Air Force Civil Engineering Support Agency at Tyndall AFB, Florida.

The next three sections of this paper address issues important to the completion of the screening phase of RAAS. They include: development of additional technology modules; integration of the ARARs screening process; and the expansion of RAAS's screening capabilities to include screening based on effectiveness, implementability and cost. In Section VI, a method to validate phase one will be discussed. The paper concludes with recommendations on how RAAS can be improved to better support the end user--the CERCLA decision maker.

III. Technology Modules

A. General

The technology module is the critical component in RAAS's method for screening technologies for applicability and effectiveness at a hazardous waste site. As was described above and diagrammed in Figures 5-7, the technology object contains a two-part representation of each clean up technology. The first part is a set of inference rules which compare the constraints of the technology to the conditions at the site. The second is a mass balance model which is invoked to determine what residual waste streams would result if the technology was applied at the site. If a technology passes both the test for applicability and the test for effectiveness, it is incorporated into a treatment train recommendation.

At present, RAAS contains modules for approximately 95 different remediation technologies. These technology modules describe the basic process (e.g. catalytic oxidation describes all types of incineration) but do not describe specific technology options for that process (rotary kiln, liquid injection). Alternative options are called "process options" in RAAS. This section of the paper describes the information necessary to include a new process option in RAAS. Following this introduction, details of three process options will be presented.

In evaluating the applicability of a remediation technology, RAAS focuses on basic parameters about the medium, the contaminants and the site conditions. These parameters are supplied by the system user in the initial session with RAAS. RAAS works with the 10 medium types shown in Table 5 and contains information on 399 contaminants divided into the 14 categories shown in Table 6. For each of the contaminants, the RAAS database contains the information shown in Table 7.

Table 5. Contaminated Media Alternatives.

Unsaturated Soil	Groundwater
Saturated Sediment	Surface Water
Sludge	Other Aqueous Streams
Particulate Solid	Organic Liquid
Monolithic Solid	Gas or Air

Table 6. Contaminant Categories.

<u>Organic Contaminants</u>	<u>Inorganic Contaminants</u>
1. Halogenated non-polar aromatics	11. Non-volatile metals
2. PCBs, Halogenated dioxins, furans	12. Volatile metals
3. Other halogenated polar aromatics	13. Other inorganics
4. Halogenated Aliphatics	14. Radionuclides
5. Other halogenated compounds	
6. Nitrated aromatics and aliphatics	
7. heterocyclics, non-halogenated aromatics	
8. Polynuclear aromatics and heterocyclics	
9. Other polar non-halogenated compounds	
10. Other non-polar organics	

Table 7. Contaminant Database Properties

<u>Property</u>	<u>Units</u>
Chemical formula	none
Chemical abstract number	none
Molecular weight	AMU
Boiling point	°C
Melting point	°C
Vapor pressure at known temperature	mm Hg
Water solubility at a known temperature	mg/L
Henry's law constant	atm-m ³ /gmole
Octanol/Water partition coefficient	none

For each technology module, logic statements describe the applicability. For example, the technology soil venting is applicable for organic contaminants (classes 1-10) with an octanol/water partitioning coefficient less than 1000 in an unsaturated soil medium. In addition to basic inference about the media and the contaminants, rules about other aspects of site conditions are included to better determine the applicability. Using the soil

venting example, additional disabling conditions include: depth to ground water less than 5 feet; hydraulic conductivity less than $1.0E-5$ m/s and soil temperature less than 15 degrees C. All of the information necessary to complete these inferences are taken from basic data either supplied by the user or contained in the RAAS databases.

More complex inference rules for applicability may be developed by performing basic calculations on the input data. Again, using soil venting, soil venting is disabled if the dissolved metal concentration in the media becomes toxic. The metal concentration parameter is 200 ppm. In order to check this parameter, RAAS sums the concentrations of all the metals identified by the user (contaminant classes 11 and 12) and compares it to the 200 ppm criterion. If the sum is greater than 200 ppm, the technology is disabled. The important issue is to provide as many accurate screening criteria as possible using the limited information available from the user and the system data.

The second phase of the RAAS method for screening technologies is to determine the effectiveness of the technology based on a set of mass balance calculations. In order to perform these calculations, RAAS takes the user information and information from its databases and develops a model of the contaminated medium. This model is held in the "cell" object shown in Figure 5 and contains some or all of the parameters shown in Table 8.

Table 8. Medium Properties.

Parameter	Units
Type of medium	None
Location of medium	None
Temperature	°K
Pressure	Atmosphere
Total Volume	m ³
Volumetric flowrate	m ³ /sec
Average particle diameter	m
Dissolved oxygen concentration	Kg/m ³
Total organic carbon	Kg/m ³
Hydraulic conductivity	m/sec
Volume fraction of solid phase	Fraction
Volume fraction of immiscible phase	Fraction
Volume fraction of aqueous phase	Fraction

Table 8. Medium Properties. Continued.

Volume fraction of gaseous phase	Fraction
Density of the solid phase	Kg/m ³
Density of the immiscible phase	Kg/m ³
Density of the aqueous phase	Kg/m ³
Density of the gaseous phase	Kg/m ³
Concentration of each contaminant in the solid phase	Kg/m ³
Concentration of each contaminant in the immiscible phase	Kg/m ³
Concentration of each contaminant in the aqueous phase	Kg/m ³
Concentration of each contaminant in the gaseous phase	Kg/m ³

RAAS models each technology as a unit process which creates one or more output streams. Figure 9 shows the unit process representation for the soil venting technology. RAAS also contains a set of mass balance equations which alter the parameters from Table 8 for each output stream. The concentration of the contaminant and any new by-products formed by the technology are held in temporary "cell" objects. These output concentrations are compared to the remediation objectives to determine if the technology is effective and should be included as a part of a treatment train.

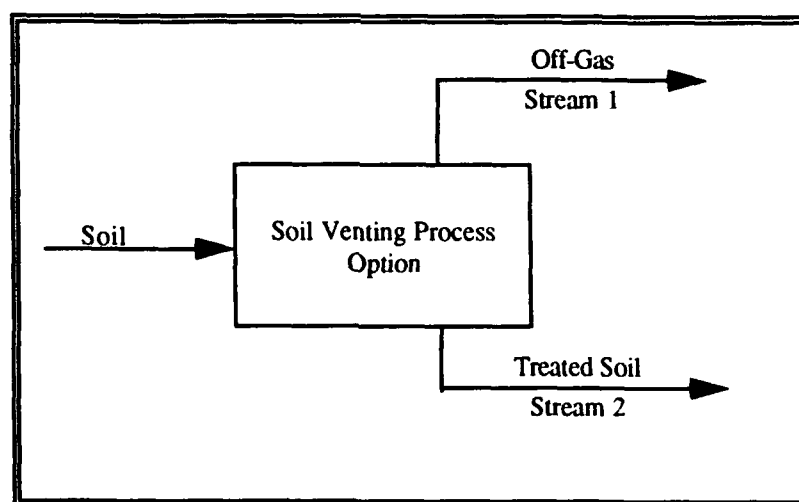


Figure 9. Mass Balance--Soil Venting.

The mass balance model for each technology makes the assumption that the process will work optimally for the conditions at the site (Battelle, 1991). In other words, the technology will work effectively if the applicability criteria described above have been met.

It is important to remember that the assumptions made by the system must be fully documented to ensure that future users will be able to verify how the system reached its conclusions.

In order to predict the outcome more accurately, RAAS often contains efficiency parameters for different contaminant classes. For example, in soil venting, RAAS indicates that the process is 95% efficient for contaminant classes 1-2 and 6-10 but only 70% efficient for contaminant classes 4 and 5. In addition, the program assumes that parameters which might vary considerably at the site (e.g. contaminant concentrations) are constant at the values supplied by the user. The ability to handle spatially distributed data is contemplated for subsequent versions of the program.

One of the challenges in representing 95 different technologies using these mass balance models is to avoid adding additional parameters about the contaminants or the media to the databases. More accurate descriptions could be developed, but the burden of developing and maintaining the additional parameters in the databases would be expensive. Therefore, the developer must look for unique ways to combine the available information to draw as many discriminatory conclusions as possible.

The remainder of this section presents three process options developed for RAAS. For each technology, the discussion includes: a description of the process including the output streams; a summary of the constraints for applicability and effectiveness; and a summary of the mass balance calculations developed for each output stream. Appendices A-C contain complete descriptions of the technology modules prepared for input to RAAS.

B. In-Situ Surfactant Flushing

Early remediation efforts at many Superfund sites where subsurface soils and groundwaters were contaminated by organics focused on "pump-and-treat" systems. These systems extracted groundwater and stripped contaminants before returning the water to the aquifer. Evaluation of the results of these efforts has shown that low solubility

contaminants which adsorb to the soil are not effectively removed by water-based extraction methods (Travis, 1990).

In-situ surfactant flushing was developed by the oil extraction industry to enhance the removal of oil from deep underground wells. More recently, it has been investigated as a method to enhance removal of low solubility organic contaminants from hazardous waste sites. Surfactant flushing is normally accomplished by pumping surfactant laden water through a saturated or unsaturated soil matrix and recovering the contaminated surfactant solution via extraction wells. Figure 10 presents a schematic of in-situ surfactant flushing.

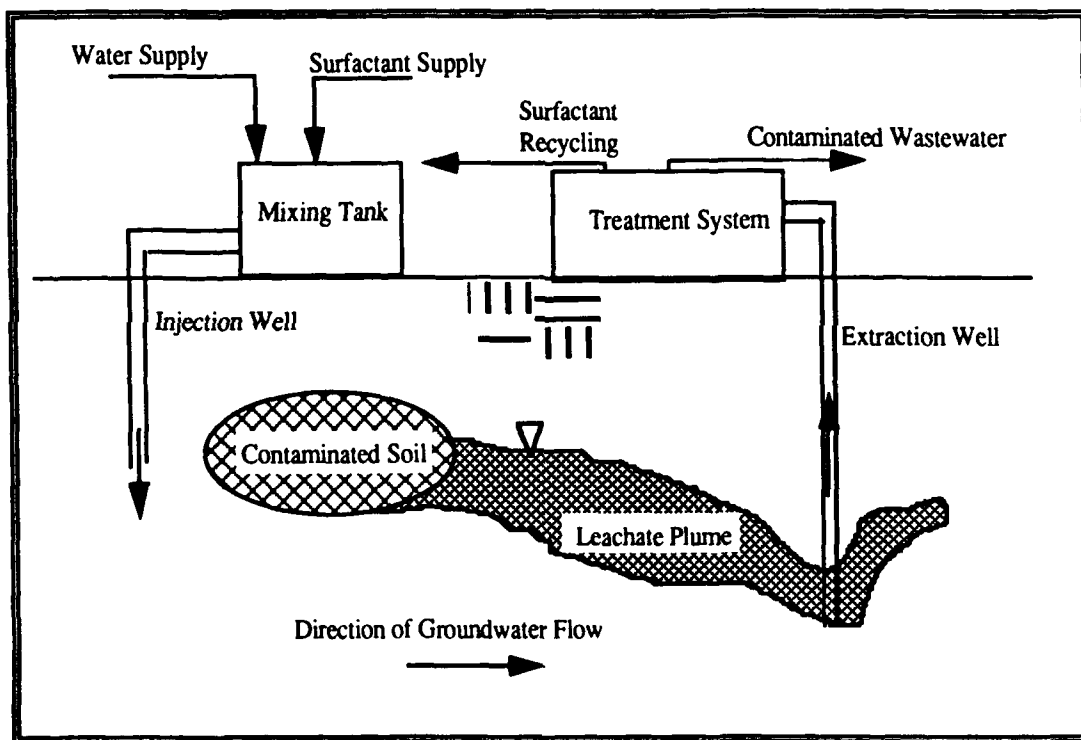


Figure 10. In-Situ Surfactant Flushing.

Research on in-situ surfactant flushing has targeted removal of organic contaminants such as PCBs which have an extremely low solubility (0.042mg/L) and a octanol-water partitioning coefficient of $\sim 60,000$ (K_{ow}) (Wilson, 1989). Others have focused on common industrial solvents such as trichloroethylene (TCE) (solubility 1100 mg/l, $K_{ow} = 200$) (Fountain, 1991). Effective surfactants must increase contaminant solubility and facilitate desorption of the contaminant from the soil.

Process Description. At the molecular level, surfactants are a class of chemicals which have a polar "head" and a long-chain nonpolar "tail". At sufficient concentrations in an aqueous solution, the hydrophobic tails associate together and the individual molecules form spherical micelles which have the hydrophilic heads exposed to the water. Compounds which have a very low solubility in water are highly soluble in the hydrophobic interior of the surfactant micelles. Experiments have shown that the partitioning coefficient for compounds between the micelle and the aqueous phase (K_m) is highly correlated with the more common octanol-water partitioning coefficient (K_{ow}) (Valsaraj, 1989). This correlation will allow screening for the use of surfactant flushing with readily available data.

In a surfactant flushing operation, the surfactant solution is pumped through pores in the contaminated soil matrix. Micelles of surfactant which pass in proximity to adsorbed contaminant allow the contaminant to desorb and become solubilized in the micelle. The process is controlled by the ability of the surfactant solution to penetrate the contaminated media and come in contact with the contaminants. In addition, the surfactant must be compatible with the contaminant and the soil.

Surfactant compatibility has been studied extensively for the purpose of enhanced oil recovery. However, this research focused on finding surfactants which reduce the surface tension between the oil and the geologic formation and allow it to flow more freely. This research did not explore the ability of surfactants to solubilize the oil. Researchers evaluating in-situ surfactant use have noted that surfactants which are highly effective at reducing surface tension may in fact be harmful if used on dense contaminants. If these contaminants are induced to flow more freely, they may migrate further down through the soil/aquifer matrix and expand the zone of contamination (Fountain, 1991). Thus, current research has focused on solubilization with a minimization of surface tension reduction (Vigon, 1989; Fountain, 1991). These studies have shown that a wide range of surfactants

are effective at solubilizing and mobilizing organic contaminants. Models developed by these investigators will be used to screen for the effectiveness of surfactant flushing.

While screening for potential use is very practical, selection of the best surfactant among the many available is a multi-faceted problem not well studied at this time. It is still an experimental technology and results to date have been highly dependent on site specific conditions. As an example, some surfactants bind readily to certain soil types at low concentrations. Surfactant losses to adsorption could represent a significant material cost and must be avoided. In addition, contaminant desorption rates are not directly related to surfactant dosage and must be evaluated on a case-by-case basis. Finally, economical use of surfactants is incumbent on recycling the surfactant solution. Several authors have proposed methods to separate the contaminant from the surfactant but no generalizations from their results are appropriate at this time (Wilson, 1991; Vigon, 1989)

Because the SARA amendments to CERCLA bias the remedy selection process in favor of permanent, in-situ treatments, surfactant flushing is a promising innovative technology. The screening criteria described below focus on the ability of surfactants to mobilize insoluble contaminants. The assumption is made that if surfactant flushing is indicated, that subsequent engineering analysis and experimentation will identify the most appropriate surfactant and dosage.

Applicability Constraints. For inclusion in the RAAS technology database, constraints are described for applicability. These constraints are then encoded into logic rules in the system. Table 9 summarizes the constraints for in-situ soil flushing.

Table 9. Applicability Constraints--In-Situ Surfactant Flushing.

<u>Media</u>
Saturated and Unsaturated Soils
<u>Contaminant</u>
Organics (Classes 1-10): $K_{ow} \geq 500$.
Inorganics (Classes 11-14): Water Solubility ≥ 0.1 ppm.
<u>Disabling Conditions</u>
Contaminant is not in-situ
Soil hydraulic conductivity $\leq 10^{-5}$ m/s
Water solubility ≥ 2500 ppm
Contaminant Concentration ≥ 5000 mg/kg

Soil flushing is applicable for both saturated and unsaturated soils. By definition, the matrix must remain in-situ for the technology to be applicable. The critical soil parameter is the hydraulic conductivity. If the hydraulic conductivity is less than $1.0E-5$ m/s, the micelles of the surfactant solution will not be able to move through the soil. Soil flushing is more effective in sandy soils but will work in clayey or organic soils with sufficient hydraulic conductivity to allow adequate flushing.

For organic contaminants in classes 1-10 (see Table 6 above), surfactant flushing is applicable if K_{ow} is greater than 500. If K_{ow} is less than 500, flushing with a water solution will be effective. Surfactants have also been used to mobilize inorganic contaminants in classes 11-14 (e.g. chelating agents like EDTA to mobilize lead). Inorganic mobilization is evaluated based on the surfactant's ability to increase the effective water solubility of the material. The criteria of a water solubility of 0.1 ppm for inorganics is based on the limited effectiveness of surfactant mobilization of metals from fine particles (EPA, 1990a).

Four disabling conditions are shown in Table 9. Of one or more of these conditions are found in the site investigation, the technology is not indicated for use. For example, if the water solubility of the contaminant is greater than 2500 ppm, a water based flushing method would be more cost effective. In addition, if the contaminant concentration is greater than 5000 mg/kg of soil, surfactant flushing is not recommended.

With a high concentration of contaminant, the soil pores will be clogged with contaminant and insufficient contaminant surface area will be available for contact with the surfactant solution.

Effectiveness Model. The second test used to screen a potential technology uses a mass balance model of the technology. For surfactant soil flushing technology module, the mass balance is represented by Figure 11. The process generates two output streams: a flush liquid laden with contaminant and the treated soil. The final contaminant concentrations in these two output streams are evaluated to determine if the technology is effective.

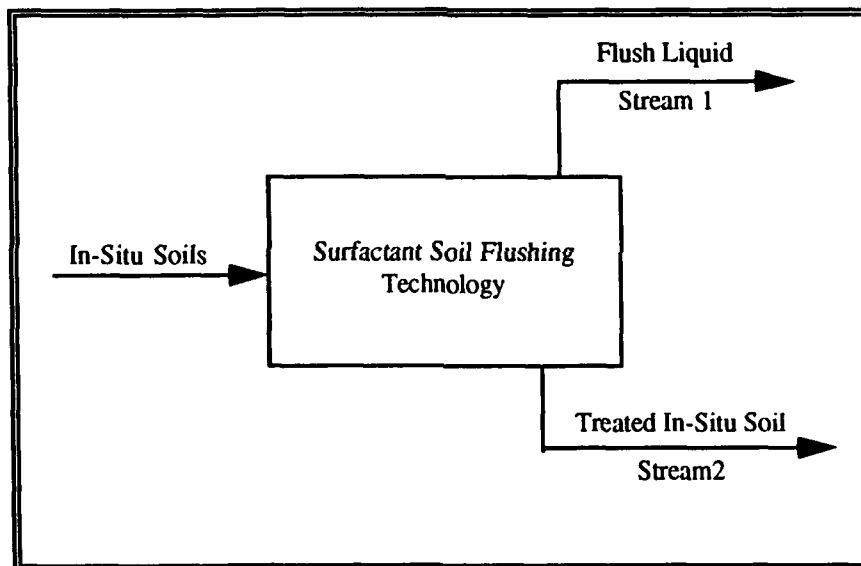


Figure 11. Mass Balance. In-Situ Surfactant Flushing.

The volume of the flush solution required is determined by estimating the number of equilibrium contacts between the contaminated matrix and a pore volume of surfactant solution required to remove the most insoluble contaminant. Separate calculations are done for organics and inorganics and the larger of the two results is used by the model as the required number of flushings. The model assumes that the surfactant flushing is done in a batch mode where equilibrium partitioning coefficients can be used. The assumption that a batch analysis will approximate the continuous flow process in the real treatment is accurate

for a first approximation of the effectiveness of the technology. Final design work would require models of continuous contaminant removal.

For both inorganic and organic contaminants, the amount of a contaminant removed by surfactant flushing is estimated from the concentration of contaminant which remains on the soil after the given number of equilibrium contacts with a pore volume of water. For inorganics, the equilibrium partitioning between the surfactant solution and the contaminant sorbed to the soil is based on the water solubility of the contaminants. No solubility enhancement by the surfactant is incorporated into the model. For organics, the model assumes that the equilibrium partitioning between the surfactant solution and the contaminant sorbed to the soil is based on K_{ow} . The surfactant effectiveness is also a function of K_{ow} . The mass balance for each equilibrium flushing is represented by the equation:

$$m = m' - v Vc$$

Where:

m = mass of contaminant in the material to be treated

m' = mass of the contaminant in material to be treated after flushing

v = voids fraction

V = volume of material to be treated

c = contaminant concentration in surfactant solution after equilibration

$$c = [c_o + K_d (C - cmc)] \frac{m'}{m' + m_{1/2}}$$

Where:

c_o = solubility of the contaminant in pure water

C = surfactant concentration

K_d = partitioning coefficient, slope of a plot of contaminant solubility versus surfactant concentration above the cmc

cmc = critical micelle concentration

$m_{1/2}$ = soil- contaminant adsorption parameter, small of adsorption is weak, large if adsorption is strong

The term $\left(\frac{m'}{m' + m_{1/2}} \right)$ is used to account for the reduction in ease of solubilization of the contaminant at low soil contaminant concentrations. At low soil concentrations, contaminants may be strongly bound to the soil by adsorption (Wilson, 1991). The parameter K_d describes the effectiveness of the surfactant. It is equivalent to the micelle-water partitioning coefficient K_m and is also well correlated with K_{ow} (Wilson, 1991; Valsaraj, 1989). Wilson used empirical data to develop the following expression.

$$\log_{10} K_m = 1.12 \log_{10} K_{ow} - 0.686$$

Wilson found a similar expression will several different surfactant-contaminant pairs (Wilson, 1991). The expressions will vary based on the contaminant and the surfactant used. Note that when the surfactant concentration is below the critical micelle concentration ($C < cmc$), the model is applicable for a water based flushing system where partitioning is based on the water solubility, c_o . In addition, the model can be used for inorganics because with $K_d = 0$, the model is based on water solubility only.

If we let,

$$A = vV[c_o + K_d (C - cmc)]$$

and write

$$m = m' + \frac{Am'}{m' + m_{1/2}V}$$

Then we can express m' , the concentration of contaminant after flushing, by the following quadratic equation.

$$m' = \frac{-(m_{1/2} + A - m) + \sqrt{(m_{1/2}V + A - m)^2 + 4 m V m_{1/2}}}{2}$$

This formula can be solved recursively n times to find the mass of contaminant left after n flushings. For the RAAS model, we want to find the number of flushings (n) required so that the concentration of contaminant only changes by 1% per wash. In order to find n , the

program must check the calculation $\frac{m_n}{m_0}$ after each iteration of the model. m_n is the mass remaining after the n th flushing and m_0 is the mass of contaminant in the soil prior to flushing. When $\frac{m_n}{m_0}$ is less than 0.01, a sufficient number of flushings has been completed.

The model selects the largest number of flushings required to remove the most recalcitrant contaminant (inorganic or organic) and then calculates the quantity of surfactant fluid used based on the pore volume of the soil matrix. The concentration of the contaminant in this fluid is calculated based on the total contaminant removed and the total fluid volume.

Figure 12 is a graph of m' , the residual soil contamination, versus N , the number of flushings, for a typical contaminant. One line shows the number of flushings without surfactant and the second shows the improvement that a surfactant might allow. The contaminant and soil parameters are indicated on the figure.

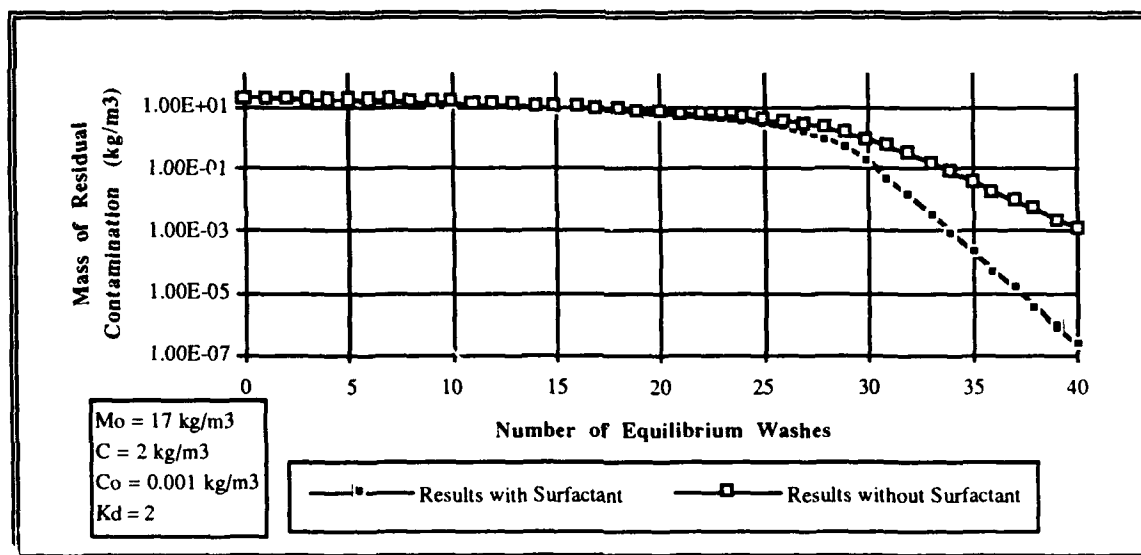


Figure 12. Performance of In-Situ Surfactant Flushing.

A detailed description of all of the parameters tracked by RAAS in the surfactant flushing module is provided as Appendix A. The appendix also discusses typical values which might be used for surfactant concentrations and partitioning coefficients in the screening model. Different partitioning coefficients should be used for different classes of

chemicals to best describe the effectiveness of surfactant use. Because of the highly site specific nature of the soil partitioning coefficients and the contaminant specific effectiveness of the surfactants, additional analysis will be required to validate the usefulness of surfactant flushing in subsequent analysis of the alternatives.

C. In-Situ Stabilization/Solidification

The stabilization/solidification of waste materials has its roots in the use of lime and later cement mixtures in the construction industry. In fact, historians trace the use of lime to stabilize road beds back to ancient Roman and Chinese practices (Barth1990b). The first real use of solidification/ stabilization for waste management was in the disposal of low level radioactive waste sludges in the 1950s. The process was used primarily to solidify liquid wastes for ease in transportation. With the passing of the Resource Conservation and Recovery Act (RCRA) in the 1970s, solidification/ stabilization became a common treatment methods for industrial waste streams.

An important distinction must be made between solidification and stabilization. Solidification is a process used to convert a liquid material into a non-liquid material. This is most commonly done by adding an adsorbant binder to remove free water from the material. Solidification does not ensure that wastes in the material are bonded in the resultant matrix. Solidification is used primarily to make a material more manageable. Stabilization is the process where a waste is converted to a more chemically stable form. The primary purpose of stabilization is to decrease the mobility of contaminants in a material which is to be landfilled. From an environmental management perspective, stabilization of the waste is the critical function.

To date, stabilization has been used predominantly to fix inorganics such as heavy metals. Some of the most common materials stabilized are bottom and fly ash from power plants. Early application of stabilization technology to organic contaminants has been unsuccessful (Weitzman, 1990a). As a result, current research is heavily focused on

determining the applicability of the process for organic contaminated wastes (Barth, 1990a).

Process Description. Basically, the objective of solidification/stabilization (S/S) technology is to contain a waste and to prevent it from entering the environment (Wiles, 1987). In order to achieve this objective, S/S performs two major functions: 1) decreases the surface area across which the transport of the contaminant may occur and 2) limits the solubility of the contaminant when exposed to leaching fluids (Weitzman, 1990b). The S/S process involves mixing a binder material (e.g. lime, cement or asphalt) with the waste material and allowing the waste to react with the binder and harden. The effectiveness of the process is dependent on the interaction between the waste and the binder system.

The S/S process can be divided into three categories based on the binding agent used. These categories are: sorption, inorganic S/S and organic S/S. Each of these categories is described below. In addition, the different field methods used to implement S/S are briefly discussed.

Sorption is primarily a solidification process. It involves adding a solid material to soak up any liquid present in the waste. Typically, non-reactive, bio-degradable materials are used in sorption processes (Barth, 1990a). Examples of sorption materials include activated carbon, anhydrous sodium silicate, clays and zeolites. In other applications, fly ash or cement kiln dust may be used. Sorbents absorb water in one of four ways. These mechanisms are: water coordinated chemically in a mineral structure, noncoordinated water bound in the mineral structure, water adsorbed to the surface of the agent and water bound in the pores of the agent. It is important to understand how the water/waste material is sorbed because this will greatly affect the leachability and stability of the solidified material.

In addition to the chemical binding characteristics of the sorbent, two other criteria are important for selecting the sorbent. First, the compatibility of the waste and the sorbent must be evaluated. Second, the quantity of sorbent required to achieve the degree of solidification must be examined. These factors will affect the quality and cost of the final

product (Barth, 1990a). The most critical factor to remember about sorption is that it is not effective in immobilizing the waste. In order to achieve stabilization, either inorganic or organic methods must be used.

Inorganic S/S is the most common form of stabilization used. The typical inorganic binders used are cement and lime. Aluminosilicate (pozzolanic) materials are often used as additives to the cement or lime to improve the strength of the matrix (Barth, 1990b). With a cement-based process, the waste material is mixed with Portland cement and sufficient water to properly hydrate the cement material. The waste is incorporated into the cement matrix as it solidifies. Many metal-bearing wastes react with the cement and form metal hydroxides which are much less soluble than the ionic forms of the metals (EPA, 1989d). Lime based processes are similar to cement, however, the lime-waste material will not form a hardened mass. The primary advantage of a lime process is that it can rapidly raise the pH of the waste matrix and precipitate metals from the waste (Weitzman, 1990c). Often, a fly ash (pozzolanic) is mixed with lime in order to provide the necessary minerals to form a stronger cement-like structure. This lime/fly ash mixture will harden much slower than a Portland cement matrix.

As with sorbents, the critical factors for selecting the inorganic binder are waste compatibility and the nature of the binding that will occur. Because lime-based treatment is typically cheaper, it is often chosen when high volumes must be treated or when high strength is not required. Through the RCRA program, numerous waste streams have been evaluated for compatibility with cement and lime based S/S processes. The inorganic S/S processes have been approved as best demonstrated available technology for eight RCRA waste streams (Barth, 1990b). These waste streams are primarily metal plating wastewaters. In addition, an analysis of Superfund Records of Decision written in 1988 found that 20% of the final decisions included some type of inorganic stabilization (EPA, 1989d).

Three different organic S/S techniques have been developed. First, asphalt has been used to microencapsulate waste. In a microencapsulation reaction, the waste is encased in the binder material but does not react with it. Second, organic polymers such as urea-formaldehyde and polystyrene have been used to microencapsulate wastes. Both asphalt and organic polymers have been used predominantly to stabilize radioactive wastes (Weitzman, 1990a). Finally, organophilic clays have recently been evaluated for their ability to actually bind with and break down organic wastes (EPA, 1989d).

An evaluation of the waste compatibility with the organic binders is especially important. Many wastes can react violently with the thermoplastic microencapsulation binders. In these process, the binder must be heated before it is mixed with the waste and numerous reactions can be induced. In addition, wastes which contain water are not compatible with asphalt. Also, many of the solvents found in wastes can dissolve the asphalt binder. Finally, many inorganic salts common in all types of waste streams can inhibit the formation of adequate encapsulation (Weitzman, 1990a). The organophilic clays are high experimental. Although they show promise, none have been used in field applications to date.

S/S can be performed either in ex-situ or in-situ processes. Ex-situ processing is most common. Typically, the waste is excavated and hauled either to an open-pit mixing area or placed in one of several mixing vessels. In open-pit mixing, a backhoe is commonly used to combine the binder and the waste. When more exact mixture conditions are required, a drum or reactor vessel is usually employed. In in-situ processing, the waste and the binder are combined on site with a backhoe or specialized equipment designed for the job. In-situ processing requires that the waste in its solidified form remain on site. Because of the quality control problems associated with an in-situ operation, only a few experimental programs have been accomplished under the US EPA Superfund Innovative Technology Evaluation (SITE) program (EPA, 1990d).

Applicability Constraints. Because the three different types of S/S processes described above have fundamentally different objectives, the constraints for each will vary. Thus each process is described separately below.

Sorption processes do not provide the stabilization necessary to protect the environment from the waste material. Although they may be used as a pre-treatment step for either inorganic or organic S/S they are not appropriate for inclusion in the S/S portion of the RAAS model. The basic sorption process is included as a general technology in the RAAS data base and therefore can be placed in a treatment train before any type of treatment.

The most significant constraint on the use of inorganic S/S is its limited ability to handle organic wastes. Organic wastes are not bound in the cement or lime matrix by any known reactions (Weitzman, 1990b). Organic contaminants can also interfere with inorganic binder setting which can lead to a weaker final product. In addition, because many organics are volatile, they are often release to the air during the excavation and mixing processes used in S/S technologies. Current restrictions on the release of volatiles to the atmosphere severely limits the applicability of these processes using conventional earth moving equipment.

Based on these difficulties, EPA guidance recommends use of one of several treatment methods to remove the organic contaminants prior to S/S treatment. Technologies suggested by the EPA include: soil washing, air or thermal stripping, chemical oxidation, use of an adsorbent and biodegradation (EPA, 1989d; Weitzman, 1990a). Additional methods recommended to increase the ability of the binder to encapsulate organics involve the use of surfactants to encase the organics to allow incorporation into the cement matrix. Again, this process does not destroy or alter the organic contaminant and it may ultimately leach from the waste (Weitzman, 1990a). Finally, the guidance recommends mixing the binders and waste in an enclosed vessel to capture any organics that are evolved.

Organic contaminants also interfere with the microencapsulation process in organic S/S. As was described above, organics can dissolve the asphalt and greatly reduce the binding ability of the materials. When the heated thermoplastics are combined with the organic waste, increased volatilization of the organics will also occur.

Because of the strong evidence that organics adversely affect both inorganic and organic S/S processes, the constraints entered into RAAS will limit the applicability of the technology to waste streams which have been treated to remove organics in all classes. Only trace residuals will be allowed. Research into better ways to combine organics in inorganic S/S processes has been called for by the EPA (Barth, 1990b) and recent articles have begun to address the issue (Pollard, 1991). In the future, this research may create processes which will allow the constraints to be relaxed.

The applicability constraints for both inorganic and organic S/S for inorganic contaminated waste streams are summarized in Table 10. For clarity, the table is divided into organic and inorganic S/S processes.

Table 10. Applicability Constraints--Solidification/Stabilization.

<u>Media</u>	
Inorganic S/S:	Liquids, sludges, solids, and soils
Organic S/S:	Dewatered sludges, soils and solids
<u>Contaminant</u>	
Inorganic S/S:	Contaminants in classes 11 and 14. Arsenic, asbestos and cement dust in class 13.
Organic S/S:	Contaminants in classes 11 and 14. Arsenic, asbestos and cement dust in class 13.
<u>Disabling Conditions</u>	
Inorganic S/S:	High conductivity soils
	High levels of halide salts, sulfur or CaCl in waste
	High water table
Organic S/S:	High conductivity soils
	Oxidizers
	High water table
	High levels of sulphates or halides in the waste

Inorganic S/S is applicable for a wide range of media. For solids and soils, the matrix should have a small, randomly distributed particle size distribution. Using the classification of contaminants created for RAAS, inorganics and classes 11 and 14 are applicable. In addition, arsenic, asbestos and cement dust, which are listed in class 13 are applicable. Inorganics in class 12 are sufficiently volatile to warrant exclusion and the remainder of class 13 include many of the salts which interfere with the binder matrix formation.

For inorganic S/S, the critical disabling conditions include: high conductivity soils, high salt concentrations and a high water table. High conductivity soils allow the rapid vertical migration of the solidifying material. High sodium halides and other inorganic salts have been shown to interfere with the binder matrix formation (Weitzman, 1990a). Finally, a high water table will subject the stabilized material to repeated leachings which may reduce the strength of the material and cause contaminant losses.

Organic S/S is also applicable for a wide range of media. However, no liquids may be treated and all sludges, soils and solids must be dewatered prior to treatment. The contaminants which are applicable are the same as those for inorganic S/S.

For Organic S/S, the disabling conditions include: high conductivity soils, a high water table, high concentrations of oxidizers such as chlorides and the presence of sulphates and halides. Oxidizers, sulphates and halides, all class 12 and 13 contaminants, interfere with the formation of the asphalt or polymer matrix. They must be avoided for effective microencapsulation (Weitzman, 1990a).

Effectiveness Model. As with other RAAS technologies, the effectiveness model for S/S will involve a mass balance model for the unit process. Figure 13 is a simple diagram of the mass balance for the process. Because S/S is a terminal treatment method, only one residual stream is mapped: the stabilized matrix. This matrix may be in-situ or ex-situ. If the output stream is in-situ, the technology may be viewed as a disposal technology.

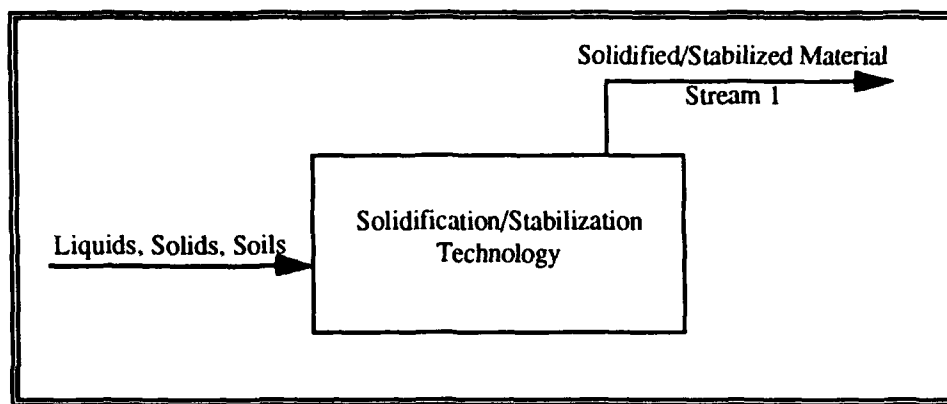


Figure 13. Mass Balance Solidification/Stabilization.

For a first approximation, the effectiveness model proposed here will assume the use of the Portland cement inorganic S/S treatment process. Because Portland cement treatment is the most effective, it will allow S/S to be selected during screening in the largest number of possible situations. The engineer can then evaluate whether another less costly S/S binder could be used in place of the Portland cement.

In a representative Portland cement design, the total amount of cement and other additives might be 30% by weight of the total waste to be treated. The total weight of the material to be treated by S/S can be calculated by summing the density times the volume of each phase. In this calculation, the gas phase will be ignored. It will be assumed that the gas phase of the contaminated matrix will be involved in the S/S process but that the amount of contaminant lost in this transfer to the atmosphere is negligible because only low volatility contaminants will be allowed past the applicability screening stage. The formula for total weight to be treated is then:

$$\text{Total Weight} = [(\rho_S)(VS_{in}) + (\rho_O)(VO_{in}) + (\rho_A)(VA_{in})](V_{in})$$

Where:

ρ_S, ρ_O, ρ_A = density in the solid, immiscible and aqueous phases respectively
 $VS_{in}, VO_{in}, VA_{in}$ = volume fraction in the solid, immiscible and aqueous phases respectively.
 V_{in} = total input volume

Thirty percent of this figure will be the weight of cement binder required. The volume of this binder material V_B can be found by dividing the weight of the binder required by its density, ρ_B .

The final waste/binder matrix will be assumed to be a solid mass. Therefore, the critical parameters for RAAS to calculate for the output stream are the volume, density and concentration of contaminant in the solid mass. The formulas for these quantities are described briefly below.

The volume of the solidified/stabilized mass will be calculated as the sum of the volume of the original soil, aqueous and immiscible phases of the waste plus the volume of the binder added. In many S/S operations, swelling occurs as the cement hardens. The effect of the swelling would be to increase the final volume to that greater than proposed in this model. For the purpose of screening for technologies, this effect will be ignored. The formula for final volume is then:

$$V_S = [(V_{S_{in}}) + (V_{O_{in}}) + (V_{A_{in}})] (V_{in}) + V_B$$

Where:

V_B = Volume of the binder material

The density of the final mass can be represented as a weight average of the densities of the aqueous, immiscible and solid phases of the waste plus the density of the binder material. The formula can be shown as:

$$\rho_S = \frac{(\rho_S) (V_{S_{in}}) + (\rho_O) (V_{O_{in}}) + (\rho_A) (V_{A_{in}}) + (\rho_B) (V_B)}{V_{S_{in}} + V_{O_{in}} + V_{A_{in}} + V_B}$$

Finally the concentration of the waste in the final matrix can be represented as the weighted sum of the concentration times the volume of the waste in the solid, aqueous and immiscible phases divided by the new volume of the material.

$$CS_i = \frac{[(CS_{in,i})(V_{S_{in}}) + (CO_{in,i})(V_{O_{in}}) + (CA_{in,i})(V_{A_{in}})] (V_{in})}{(V_{in}) [(V_{S_{in}}) + (V_{O_{in}}) + (V_{A_{in}})] + V_B}$$

Where:

$CS_{in,i}$, $CO_{in,i}$, $CA_{in,i}$ = Concentration of the contaminant in the solid, immiscible and aqueous phases respectively

Using these expressions for the critical parameters, the model can determine the volume of the final solidified mass and the concentration of the contaminants in the mass. The information is compared to regulatory constraints and to the clean up objectives defined by the RAAS user to determine if the technology should be included on the list of potential remediation technologies. If S/S is included, the information is supplied to the user for use in further evaluations. Appendix B provides a detailed discussion of the applicability and effectiveness criteria for S/S.

D. Fluidized Bed Incineration

Incineration technology is well developed and employed by a wide number of industries to destroy conventional wastes. Unfortunately, like solidification/stabilization, the complex chemistry of incineration is highly unpredictable due to the large number of reactions which take place in the combustion system. This uncertainty over the by-products of incineration has caused extreme opposition to the use of incineration systems to destroy hazardous wastes. Despite the opposition, many scientists still pursue improvements to incineration systems because of their proven ability to decrease both the toxicity and the volume of waste materials.

Although much of the discussion below will focus on the fluidized bed furnace, an incineration system includes more than just the combustion chamber. An incineration system must also prepare the waste for the combustion chamber and handle the by-products of combustion from this furnace. Figure 14 is a schematic of a complete incineration system. The system shown can be evaluated as three components. First, the waste processing and feed stage is used to modify the waste material to make it compatible with incineration. The most important concerns in waste preparation are reducing the particle size of the waste and blending the waste to create a material with a uniform heat content.

The second stage is the combustion chamber itself. The critical factors in the combustion chamber are often called the three Ts of incineration: time, temperature and turbulence (EPA, 1988a). The description of the fluidized bed process below will address the three Ts. Finally, because incineration does not fully combust the wastes, the last stage of the system is the residue handling system. This system consists of both air pollution control devices and a system to handle the ash from the combustion chamber.

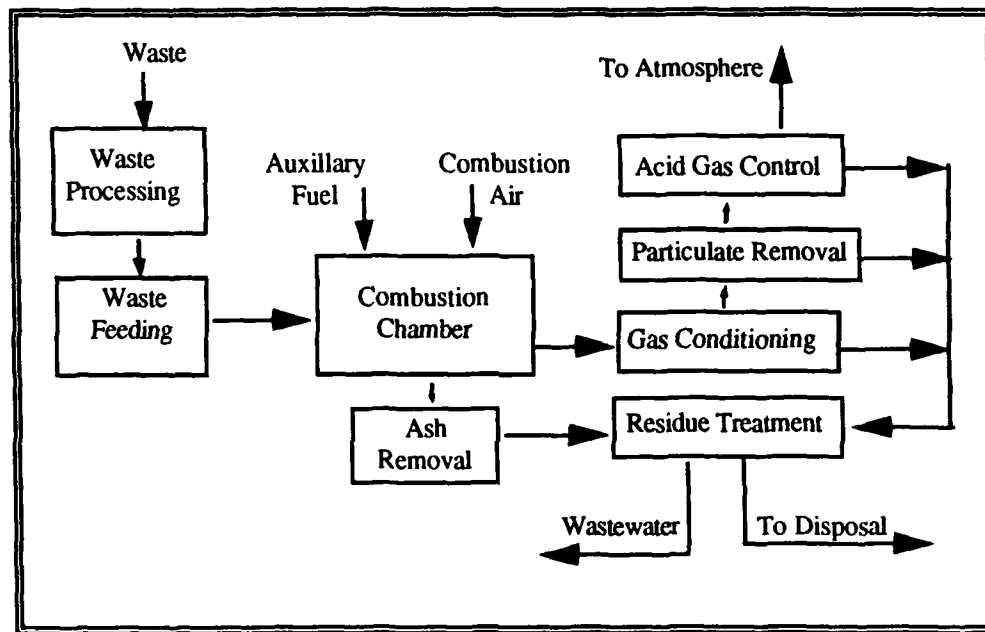


Figure 14. Incineration System Schematic.

The performance of an incinerator is based on its effectiveness at destroying organic contaminants. These critical contaminants, called principal organic hazardous constituents (POHCs), are measured in the input material and in the output gases and ash. Current regulatory standards require that 99.99% of the POHCs be destroyed by incineration. In addition to POHCs, incinerators are evaluated based on their output of carbon monoxide and acid gases.

A majority of the standards for incineration of wastes have been developed under the RCRA program. RCRA waste incinerators typically are permitted to burn a very specific waste stream and can control the input to the incinerator to meet the strict emissions standards. By contrast, in the CERCLA program, the waste materials are much less

homogeneous and are often less well characterized for trace constituents. However, by the regulations, incineration of CERCLA wastes must meet the strict RCRA standards in order to be operated. Because of the difficulty in accurately characterizing the CERCLA wastes, many RCRA permitted hazardous wastes incinerators do not accept CERCLA wastes.

One of the major requirements of the SARA amendments to CERCLA was to bias the treatment technology selection process toward on-site treatment. This policy, coupled with the reluctance of RCRA incinerators to accept CERCLA wastes, has led to the development of mobile incinerators. These systems are scaled-down versions of the large fixed-site systems that are transportable by truck or rail. The most common material to be incinerated at Superfund sites are soils (80% of the RODs for incineration were for soils, EPA, 1988a). Because of its success with soils, the rotary kiln system has been the most common mobile system. The limited mechanical reliability of rotary kiln systems has caused EPA to look for other less complicated systems capable of handling soils. The fluidized bed system has been studied for this purpose.

Process Description. The fluidized bed incinerator consists of a bed of inert granular material heated to high temperatures and "fluidized" by the introduction of high pressure gases from below the bed material. Figure 15 depicts the fluidized bed incinerator design. One of the primary advantages of the fluidized bed design is that it has few moving parts (McFee, 1985). As is shown in the diagram, waste is introduced into the system directly into or just above the fluidized bed. Heavy materials that settle through the bed and lighter materials that are forced out of the combustion chamber are collected for disposal and the off-gases are treated with typical incineration pollution control devices.

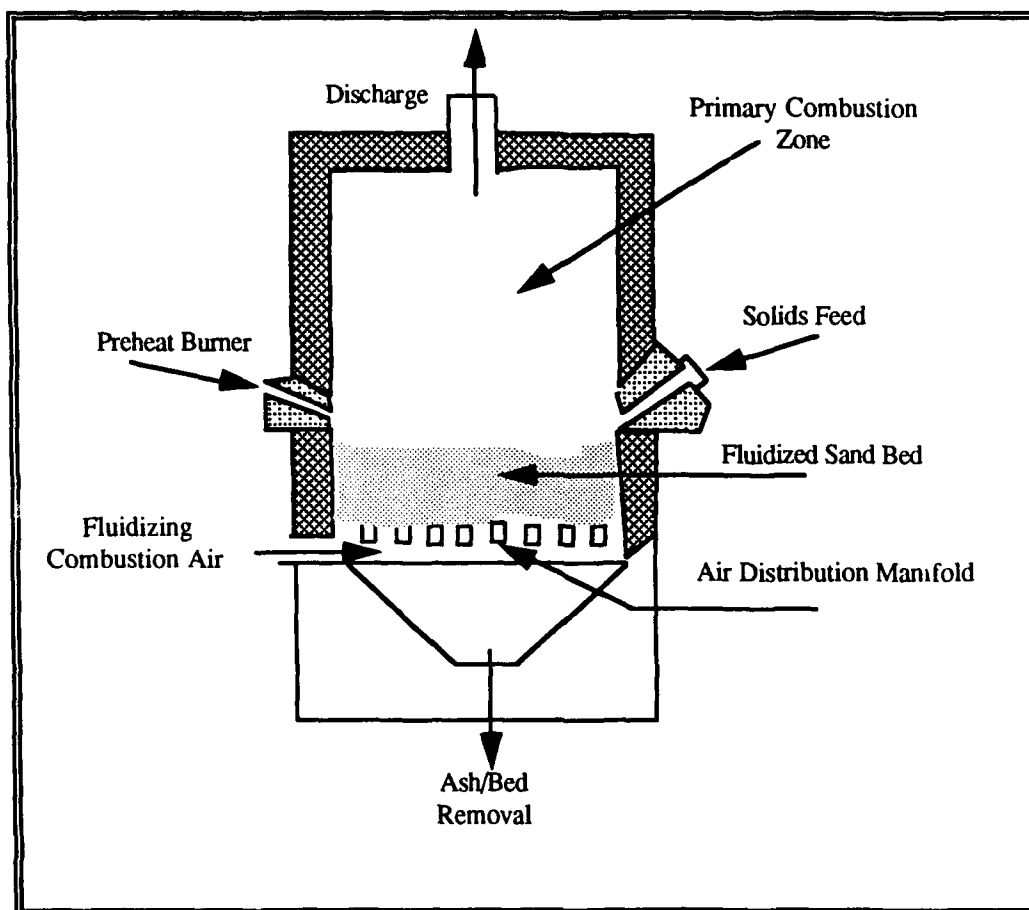


Figure 15. Fluidized Bed Incinerator.

The primary design advantage of the fluidized bed system is the bed itself. The hot bed material provides excellent mixing and heat transfer conditions. This effective turbulence allows fluidized bed systems to be operated with less excess air and often at lower operating temperatures (Brunner, 1984). Design considerations involve selecting a bed material, typically a sand, that is compatible with the waste and is properly sized for good interparticle contacts. McFee *et. al.* discuss the design of a fluidized bed system specifically for soil combustion (McFee, 1985).

The bed material is also the source of most of the difficulty with fluidized bed systems. Certain waste materials, especially salts, tend to melt in the bed and can cause agglomeration of the bed particles (Brunner, 1984). When agglomeration occurs, the mixing and heat transfer properties of the bed are diminished. In addition, particles that

remain suspended in the bed at combustion air velocities are very difficult to remove from the system (McFee, 1985).

The final major challenge in the use of fluidized bed systems is waste preparation. For current designs, all particles must be reduced to less than 3 inches in diameter prior to injection into the bed. This level of size reduction requires that expensive and sometimes unreliable shredding and crushing equipment be used. In addition, the waste must be mixed sufficiently to provide a uniform input fuel to the system. Variations in BTU value and in water content of the input material can cause serious deviations in the composition of the output of gases (EPA, 1990a). These variations often result in regulatory violations. Widely varying input materials will also require the use of additional auxiliary fuel to ensure adequate destruction (EPA, 1988c). These waste handling problems can quickly destroy the cost effectiveness of the fluidized bed system.

Applicability Constraints. The most significant constraints on the use of fluidized bed incineration are based on the properties of the waste materials. Materials that will foul the bed must be avoided. Alkali metal salts and halogens tend to melt at high temperatures in the bed. They become "sticky" and cause particles of the bed to adhere to one another. The result is a loss of fluidization and loss of the high surface area for interparticle contact that is the heart of the fluidized bed process.

According to McFee the salt concentration in contaminated soils is not a limiting factor for fluidized bed processes. He notes that the salts will be carried out of the combustion chamber with the flue gas at a sufficient rate to avoid bed fouling (McFee, 1985). To realistically screen soils for this technology, the salts and halogen concentrations should be determined in laboratory investigations. Table 11 summarizes further the applicability constraints for fluidized bed incineration.

Table 11. Applicability Constraints--Fluidized Bed Incineration.

<u>Media</u>
Sludges, Solids, Liquids, Soils
<u>Contaminant</u>
Organics (Classes 1-5): Concentration of halogens < 8%
Organics (Classes 6-10): Acceptable.
Inorganics: Not acceptable
<u>Disabling Conditions</u>
Salts. Concentration of alkali metal salts > 5%, halogens >8%.
Large particles sizes which can not easily be reduced.
High moisture content waste/low heat capacity.
High density wastes. Density > 3 Kg/m ³ .
Highly chlorinated wastes.
High concentration of trace metals.
Highly variable waste stream.

Fluidized bed incineration processes are applicable for liquids, sludges, soils and solids. The process requires that any of these materials be excavated and delivered to the incineration system. The critical parameters for any of these materials are their moisture content and their heat capacity. The moisture content can be determined directly from the data supplied by the RAAS user. However, the heat content will have to be inferred from the contaminant class and the concentration of the contaminant in the waste matrix. These parameters will determine the amount of auxiliary fuel required by the system.

Incineration is not an effective method to destroy inorganics and heavy metals. Therefore, incineration is excluded as a primary treatment for these wastes. When the metals are trace contaminants in an organic waste stream, their concentration must be limited to prevent them from being volatilized and released in the stack gas. Current RCRA regulations require that the metal concentration in incinerator input be limited so that a 99.99% removal efficiency of the metal can be achieved. EPA guidance also states that alkali metal salts should be less than 5% by dry weight (EPA, 1988c). When excessive chlorinated or sulfonated waste are present, high concentrations of acid gases can be released. Although the air pollution control equipment can remove a majority of this acidity, the concentrations of Cl, and SO₄ in the waste must be limited.

Particle size is also an important criteria. All particles must be reduced to 2-3 inches in diameter prior to incineration. If this criteria is not met, additional shredding capacity may be required. The variability of the waste stream is also very important, however, the RAAS system does not have a good method to describe the variability of the stream. Variability will have to be evaluated after screening. Finally, high density contaminants will tend to fall through the bed material quickly. These materials must be reduced to very small sizes to ensure that adequate heat transfer can occur.

For the screening of chemicals in RAAS, the RAAS contaminant classifications will be used. Classes 1-5 are halogenated organic whereas classes 6-10 are non-halogenated compounds (See Table 6). High concentrations of contaminants in classes 1-5 must be evaluated for excessive halogenation. While the contaminants will be oxidized in the combustion process, the amount of acid gases released may be excessive. EPA guidance suggests halogens should be less than 8% by dry weight of the total contaminant mass (EPA, 1988c). For RAAS, a concentration calculation will check this 8% criteria.

Effectiveness Model. The mass balance for an incineration system is complicated by the need to use both auxiliary fuel and excess air to facilitate proper combustion. Figure 16 is a schematic of the mass balance for the fluidized bed incineration. The schematic assumes that the air pollution control system is a part of the incinerator for the mass balance. There are four input streams: waste, excess air, scrubber water and auxiliary fuel. The output streams include: off gas, fly ash, scrubber water and bottom ash. Spent bed material can be included with the bottom ash for analysis.

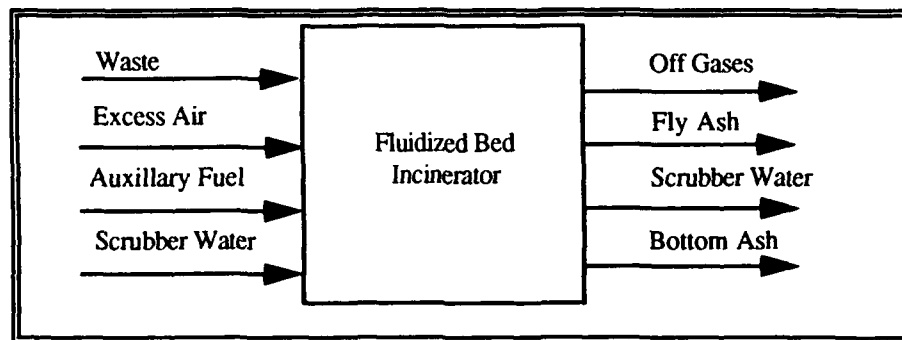


Figure 16. Mass Balance--Fluidized Bed Incinerator.

From the perspective of technology screening and development of treatment trains, the off-gas can be assumed to meet regulatory standards. Its discharge to the atmosphere will be its final disposal. For ease of calculation, the bottom and fly ash components can also be combined. The resultant mass of ash will require further processing before disposal to ensure that any residual contaminant and trace metals are stabilized. Finally, the scrubber water will entrain ash material and be acidified by the acid gases. It will also require treatment before ultimate disposal.

At the screening level, numerous assumptions must be made to allow for a reasonable mass balance calculation. These assumptions include:

- a. quantity of excess air used
- b. heat content of the waste material
- c. heat content and quantity of auxiliary fuel required
- d. resultant ash fraction of the combusted material
- e. partitioning of the ash content between bottom ash, fly ash, scrubber water and emissions
- f. quantity of scrubber water and its resultant pH
- g. destruction and removal efficiency of the incinerator
- h. partitioning of the residual contaminant between the flue gas and the ash
- i. all trace metals will be found in the ash

By assuming an ash fraction and a partitioning of the ash, one can calculate the concentration of the contaminant in the ash based on the destruction efficiency of the unit. For any permitted incineration unit, the destruction efficiency must be 99.99% except for the case of PCBs where destruction efficiency must be 99.9999%.

Focusing on the resultant ash material, the critical parameters to be calculated are the volume and mass of the ash and the concentration of contaminants in the ash. These

parameters will be needed so that further treatment modules can determine the proper technology for disposal. Oppelt notes that the quantity of ash generated by hazardous waste incinerators is highly variable (Oppelt, 1987). In addition, he notes that very low concentrations of organic contaminants have been found in ash from incinerators. These results indicate that the high efficiencies are based primarily on destruction of the organic contaminants rather than removal (Oppelt, 1987). Calculations for various output parameters for the ash residue stream are give in Appendix C.

IV. Applicable or Relevant and Appropriate Requirements

The technology modules described in section III are used to determine the technical applicability and the technical effectiveness of a remediation technology. By using encoded decision logic and a mass balance model, RAAS can provide feedback on the technical potential of unit processes and suggest ways to arrange the unit processes in treatment trains to meet the clean up objectives at a Superfund site. In the remedy selection process for a Superfund site, technological capability is only one aspect of the complete decision. The remedy for a site must also meet regulatory and economic criteria as well as be acceptable to the public. Applicable or Relevant and Appropriate Requirements (ARARs) are the collection of federal, state and local laws, codes and regulations which have a bearing on remedy selection at a site. As will be discussed below, the laws and regulations which constitute the ARARs for a site can be based on the chemical contaminants at the site, the location of the site and the specific remedial technology to be used at the site. In essence, an evaluation to ensure that a remedy will meet all potential ARARs is a determination of "regulatory applicability" of a potential treatment train. In order that RAAS properly represent the technology screening decision process, it must specifically address the ARARs issue.

This section will explain the EPA guidance on ARARs evaluation in remedy selection and examine how RAAS can model the decision process. First, the importance of ARARs will be discussed and then the obstacles which make ARARs evaluation difficult will be presented. Next, the method that RAAS will use to address the problem will be delineated. The long range plan for RAAS will fully execute ARARs evaluation by integrating RAAS with an ARARs expert system under development by EPA. Unfortunately, for the RAAS technology screening tool released in 1992, the EPA software will not be available. It is not scheduled for release until 1993. The paper will describe the

short term problems created by this development and then present two solutions to best include ARARs evaluation in the early phases of the program.

A. ARARs in Remedy Selection

Background. At first glance, the issue of ARARs applicability in remedy selection appears straightforward. In Figure 3 above, compliance with all ARARs was identified as a threshold criteria for detailed analysis of alternatives in the feasibility study. By this definition, if a proposed remedy can not meet an ARAR, it is removed from further consideration. In order to evaluate a potential remedy with respect to ARARs, the consultant must only list the ARARs applicable for a given remedy at a site and compare the proposed alternatives to them. In fact, the identification and application of ARARs at a site is one of the most controversial aspects of the RI/FS process.

In the original version of CERCLA, Congress did not specifically state how the requirements of other environmental and public health laws would be applied to a remediation effort (Smith, 1988). In addition, CERCLA was not specific about the extent of cleanup that would be required at a site. The standards were to be promulgated as a part of the National Contingency Plan by the EPA. Starting with a lack of guidance, EPA made the determination in the 1982 NCP that no national cleanup standards would be issued. Instead, clean up standards would be determined on a site specific basis. The RI/FS process thus evolved to make these site specific remedy decisions.

Because the regulations lacked minimum standards and were ambiguous about which standards must be applied at a site, EPA was sued by the *Environmental Defense Fund* and the State of New Jersey seeking better guidance. In a settlement agreement prior to trial, EPA agreed to issue more specific guidance. The guidance was called CERCLA Compliance With Other Environmental Statutes Policy and was incorporated into the 1985 revisions to the NCP. In the policy, the term ARARs was coined and legal definition of

"applicable"⁷ and "relevant and appropriate"⁸ were set. To complicate matters, the policy identified five potential reasons to allow the ARARs to be waived.

Based on the policy, at each site, the EPA would identify all potential ARARs and then apply the legal definitions to determine those that were justified at the site. The remedy would be required to be in accordance with those standards selected. EPA then set out to prepare manuals to standardize the ARARs review process.

In the SARA amendments to CERCLA, Congress rectified its 1980 error and specifically addressed the applicability of other laws in setting cleanup standards for a site. The amendments codified the site specific analysis principles developed by EPA and made compliance with the selected ARARs a threshold criteria for remedy selection. Congress also codified the complication of waivers. They identified six potential reasons to allow the ARARs to be waived.⁹

In essence, the law states that all federal, state and local regulations potentially available at a site are applicable until proven otherwise. To give an appreciation for the number of potential standards, Table 12 lists a portion of the guidelines identified as potential sources of ARARs in the 1990 NCP (EPA, 1990c). The legal definition of "applicable" and "relevant and appropriate" must be applied to each potential ARAR and a determination of applicability made. Those ARARs which are applied at a site determine in part how clean the site will be left after remediation.

⁷Applicable requirements means those cleanup standards, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal environmental or state environmental or facility siting laws that specifically address a hazardous substance, pollutant, contaminant, remedial action, location or other circumstance found at a CERCLA site. 40 CFR 300.5.

⁸Relevant and appropriate requirements means those cleanup standards, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal environmental or state environmental or facility siting laws that, while not applicable to a hazardous substance, pollutant, contaminant, remedial action, location or other circumstance found at a CERCLA site, address problems or situation sufficiently similar to those encountered at the CERCLA site that their use is well suited to the particular site. 40 CFR 300.5.

⁹Waivers will be discussed in detail below.

Table 12. Potential Sources of ARARs.

<u>Federal Requirements</u>	<u>State Requirements</u>
EPA Programs Resource Conservation and Recovery Act Clean Water Act Toxic Substances Control Act Wetlands and Floodplains Rules Radiation Protection Rules Other Federal Laws National Historic Preservation Act Endangered Species Act Wild and Scenic Rivers Act	Radiation Programs Surface Water Quality Programs State RCRA Rules State Groundwater Programs State Clean Air Act Rules State Air Toxics Rules
All federal and state programs list have advisories and guidance documents which should be consulted for program details. The advisories and guidance documents are also ARARs.	

ARARs are serious business. The difference between cleaning a contaminated groundwater to 5 ppm vs 10 ppm of a contaminant can mean millions of dollars of additional cost to a responsible party. To those who developed the standards, any relaxation of the clean up level is a potential threat public health and to the integrity of the program. In the preamble to the 1990 revision to the NCP, comments on the issue of ARARs filled some 25 pages. By contrast, the discussion of the other changes to the RI/FS regulations required only 34 pages.

The most significant "other law" which CERCLA must address is RCRA. Because RCRA has standards for all aspects of handling hazardous waste generated in current operations, it has many potential standards which might apply to the clean up of an abandoned waste site under CERCLA. One of the most vexing issues arises when a CERCLA remedy proposes disposal of treated wastes at a RCRA approved landfill. If this type of remediation is chosen, all of the RCRA restrictions on land disposal apply. Conversely, if a similar CERCLA waste will be disposed on the CERCLA site, then the law may be interpreted to eliminate some of the requirements. While this policy is

consistent with promoting on-site treatment of wastes, it opens the process to round after round of litigation in which responsible parties attempt to have the minimum standards applied to their site. Compliance with the other major environmental statutes is less complicated than with RCRA, however, the number of incongruities among the laws has haunted the EPA.

The major tool that the EPA has developed to help clarify the ARARs in a given jurisdiction is the Inter-agency Agreement (IAG). In an IAG, the EPA region, the state and any local jurisdictions which have standing negotiate a set of roles and responsibilities for the management of any Superfund sites within their mutual jurisdictions. On federal facilities, a similar instrument, called the federal facilities agreement (FFA) is negotiated among all concerned parties. Even with a current IAG, the ARARs for each site must still be analyzed for applicability.

The ARARs for a site are formalized in the Record of Decision for the site. Thus, the final ARARs are ultimately determined by negotiation. Each responsible party evaluates the precedents and attempts to assure that it has the most lenient standards available.

Before discussing the way in which RAAS will address the ARARs evaluation process, it is useful to briefly summarize the ARARs identification process. EPA has issued extensive guidance on the process in an attempt to standardize the application of the legal definitions. The following material is summarized for the EPAs guidance called the "CERCLA Compliance with Other Laws Manual." (EPA, 1988d).

The ARARs Identification Process. In order to help categorize potential ARARs. EPA identifies three types of ARARs: chemical-specific, location-specific and action-specific. Chemical specific ARARs are rules that place a health-based limit on the quantity on a chemical that can be released to the environment. Examples of chemical specific ARARs include maximum contaminant levels (MCLs) under the Safe Drinking Water Act or Federal Water Quality Criteria (FWQC) under the Clean Water Act. Location-specific ARARs are restrictions against action in some location because of the special

character of the area. Examples include restrictions on use of wetlands or incinerator siting criteria developed by a state. Action-specific ARARs are typically rules on how different remediation technologies shall be operated. RCRA closure rules for landfills as well as Clean Water Act rule on waste water pre-treatment are examples of action-specific ARARs.

In the Compliance with Other Laws Manual, EPA has developed tables that identify all of the federal ARARs. The tables are broken into these three categories. Many states that have extensive environmental laws which differ from the federal standards have also developed tables of ARARs. Once the reconnaissance work at a site is complete, the consultant can prepare a site specific listing of potential ARARs for the site. This list is usually reviewed and commented on by the regulatory agencies early in the process. The difficulty arises when the legal definitions (see footnotes above) are applied to the potential list and the actual determination of applicability is made.

In order for a requirement to be applicable, the statutory or regulatory provisions of the requirement must be compared to the pertinent facts about the site and the response action under consideration. If all prerequisites for the requirement are met, then it must be identified as an ARAR. Information about the prerequisites for most federal laws and regulations are provided in the Compliance Manual. The determination of "relevant and appropriate" is more subjective than the determination of applicability. According to CERCLA, only those requirements that are both relevant and appropriate must be followed. In the EPA guidance, relevant and appropriate are defined by the following two statements: 1) the requirement regulates or addresses problems or situations sufficiently similar to those encountered at the CERCLA site (relevance) and 2) the requirement is appropriate to the circumstances of the release or threatened release such that its use is well suited to the particular site (EPA, 1988d). Clearly, these judgements are highly subjective and may be reviewed by all of the commenting agencies as well as the public prior to the formal Record of Decision for the site.

In summary, Figure 17 identifies all of the places where ARARs should be addressed in the CERCLA process. The iterative nature of the process means that the final set of ARARs is refined again and again right up to the ROD. In fact, the figure notes that ARARs may be updated and reevaluated during design and operation of the remedial action.

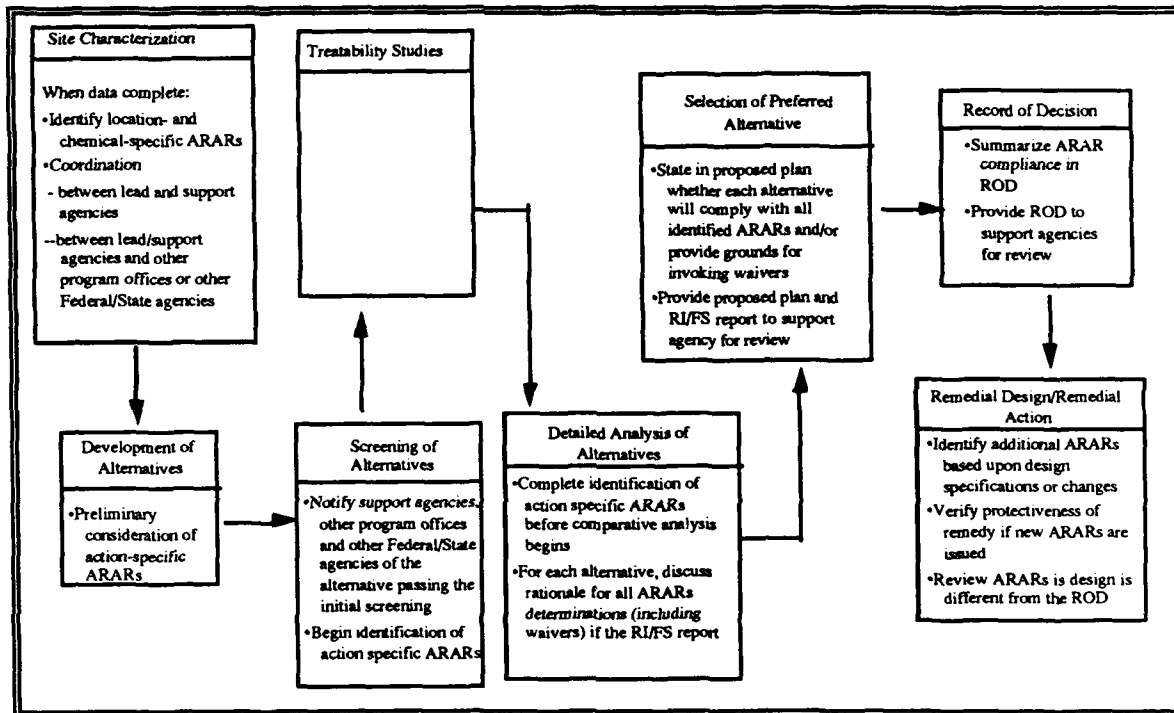


Figure 17. ARARs in the CERCLA Process.

Simulating the ARARs Evaluation Process. From a cursory review of Figure 17 and Table 12, it is easy to see that modeling the ARARs evaluation process with an expert system is a major project. First, the decision rules used to properly determine whether a law or regulation is "applicable" or "relevant and appropriate" are subjective. They are based on site-specific interpretations of the regulations. In addition, they are based on an ever changing set of precedents that can potentially change with each new record of decision. Second, the database required to represent all three types of ARARs, chemical, location and action-specific criteria, is a massive. In 1988, there were 29 MCLs, 95 FWQC, 6 NAAQS and 10 NESHAPS in federal environmental regulations and literally

thousands of state-specific criteria (Smith, 1988). Like the laws themselves, the criteria are constantly being reviewed and updated. Proper maintenance of an ARARs database to capture these changes in a time sensitive way is an expensive proposition.

Properly capturing the ARARs evaluation process is probably the most significant obstacle for RAAS to overcome in order to reach its long-range goal of automating the full remedy selection process. Proper consideration of the ARARs process is also critical to RAAS's first goal--screening remediation technologies. ARARs are important in technology screening for two reasons.

First, regulatory applicability is as important as technical applicability when selecting the final remedy. If a proposed technology will not be accepted because of jurisdictional or action-specific reasons, identification of the treatment technology by RAAS will unnecessarily burden the RAAS user. Considerable resources could be wasted in the evaluation of a recommended technology only to have state or federal regulatory personnel discard it on an ARAR's technicality. Failure to identify a potential ARAR is also a major concern. If an ARAR is realized after the remedial design has begun, costly modifications and administrative proceedings could be required (Greathouse, 1991). Delays of this type are costly both in terms of time and in terms of public health.

Second, screening based on action-specific ARARs is essential for RAAS to create a credible technology list. Many of the potential technologies will be deemed technologically feasible. Nevertheless, many will be excluded based on site-specific conditions. RAAS must capture the critical action-specific exclusions in order to create a realistic list of applicable technologies. Credibility is a critical issue for expert system output. Regulatory agencies are not going to be comfortable with the recommendations of a system that does not consider basic exclusionary criteria.

RAAS ARARs Strategy. Having established that ARARs evaluation is central to the RI/FS process and that it must be properly represented in the RAAS methodology, we now turn to the specific procedures that RAAS will use to handle ARARs. In the long-

run, RAAS will be integrated with an expert system called ARARs Assist which will perform the ARARs evaluation process. RAAS will pass site information and proposed technical options to ARARs Assist and it will return information about the potentially applicable ARARs for the option. This information will be integrated into the inference processes RAAS uses to make a final remedy selection.

ARARs Assist is currently being developed by the US EPA in conjunction with the Department of Energy and the US Army Corps of Engineers (EPA, 1991b). The database for ARARs Assist is the Computer-aided Environmental Legislative Data System (CELDS). CELDS was developed by the Corps of Engineers in the 1970s to support their environmental work. Efforts are currently underway to expand the database to include relevant ARARs information. The inference mechanism for the ARARs-Assist system is being developed by the EPA Risk Reduction Engineering Laboratory. The goal of ARARs Assist is to generate a definitive list of potential ARARs and to describe the context in which the rule, regulation or standard is applicable.

In a paper EPA prepared to describe the inference mechanism for the ARARs evaluation tool, they noted that the ARARs screening process is amenable to the expert system paradigm. The problem has both the need for rule-based inferencing and the need to represent the knowledge of experts (in this case legal experts). This information must be shared among widely disperse users. Consistency is essential. They also noted that the ARARs screening process pushes the limit of automated decision support. The size of the databases required to represent all of the possible ARARs is large. In addition, the knowledge that must be encoded is highly subjective. They cited difficulty in finding sufficient experts to accurately document the process. Finally, they cited the challenges that updating and maintaining the system will represent (Greathouse, 1991). These comments further support the earlier statement that the ARARs process is the most difficult task for RAAS.

As was mentioned above, the ARARs Assist system will not be available until at least FY 1993. Until that time, RAAS must capture the basic features of the ARARs process which are essential to the screening of remedial alternative within its own inferencing capabilities. The structure of the RAAS databases is amenable to inclusion of some basic ARARs within the program. RAAS can consider all three types of ARARs.

RAAS can account directly for the basic chemical-specific constraints. For example, if the site has a groundwater cleanup requirement, it is likely that a FWQC or a MCL will have been established for the contaminant. The output of the mass balance models for each technology can be compared to these numerical concentration standards and a determination made about the applicability of a technology. The numerical criteria could be part of the contaminant database or in a separate database cross-referenced by contaminant.

The RAAS technology module can also check for basic issues of "regulatory applicability" when it checks for technical applicability. For example, the technology module for incineration could contain action-specific criteria like the types of pollution control required in different jurisdictions. Similarly, many of the action-specific constraints on disposal technologies could be incorporated directly into the technology module. Finally, a majority of the location-specific criteria could be screened with a few basic questions of the user about the site (e.g. Is the site a wetland? or Is the site on a historical register?)

Excluding technologies on basic criteria is not sufficient, however, to ensure that RAAS will give useful advice on screening remedial technologies. The primary weaknesses in this direct approach are associated with chemical and action-specific ARARs.

Most chemical-specific ARARs are Safe Drinking Water Act or Clean Water Act criteria that apply to chemical concentrations at the water tap or specific discharges of chemicals into the environment. Therefore, when applied at a CERCLA site, they are only

applicable under very specific conditions. For example, a MCL is really only applicable when the contaminated groundwater is being used directly for drinking water. The use of a single MCL also assumes that there are no interactive effects among the contaminants at the site which might heighten or attenuate the health effects of the contaminant in question (Smith, 1988). Finally, if the remedy selected does not discharge the contaminant off of the CERCLA site, the ambient FWQC or MCL again may not be wholly applicable. To exclude a potential technology based on these tenuous criteria may discard a perfectly useful, cost effective cleanup tool.

Application of action-specific criteria out of context can also incorrectly qualify the use of a potential remediation technology. Most potential action-specific ARARs are RCRA guidelines on how to operate a particular remediation technology. RCRA guidelines are particularly voluminous for incineration and land disposal technologies but have been developed for any treatment technology commonly used in industrial waste treatment operations (40 CFR 260 ff). Automatic exclusion based on an overly restrictive RCRA criteria unnecessarily limits the pool of potential technologies. If included in the screening, further evaluations may find the criteria outside the definition of "relevant and appropriate." Ignoring these criteria in screening again creates the potential for an unwieldy list of technologies that has no usefulness.

Finally, a general reliance on the chemical and action specific criteria which can be encoded based on numerical values or logic inference can misrepresent the criteria for the most common CERCLA site medium. None of the numerical criteria identified as ARARs are directly applicable to contaminant soil (soil 80% of medium, EPA, 1991a). EPA Records of Decision for contaminated soils are based on the results of health-based risk assessments where contaminant concentrations at the site are translated to contamination levels for exposed individuals. The risk assessment uses transport and fate models to determine a hypothetical concentration in the medium which the SDWA, CWA and CAA standards can be applied. Clearly, an application of an MCL at a site far removed from an

exposed population will be unduly restrictive. This restrictive application of ARARs would defeat the purpose of RAAS in attempting to suggest a wide range of technologies that the narrowly focused human expert might fail to consider.¹⁰

RAAS ARARs Method-Technology Screening. Given these constraints on the straightforward use of numerical chemical-specific requirements and action-specific standards, the RAAS methodology for the screening phase must go beyond inferences based on the criteria only. One of the basic steps that RAAS takes is to allow the user to determine the level of cleanup as program input. If the RAAS user had the benefit of a risk assessment that gave the residual contaminant concentration that would be allowed for a given level of risk, they could enter that concentration into the program. RAAS would then use this updated criterion to evaluate the effectiveness of a proposed treatment train. While this feature allows the program to consider values other than the regulatory standards, it still focuses on a fixed cut off that will exclude technologies that may fail by some small amount. RAAS must have a means to consider the likelihood that a given technology will meet the clean up goal when the numerical first approximation indicates that the technology will fail.

Because it must ultimately make a decision about the effectiveness of a technology based on a numerical criteria, RAAS has the potential to create very long treatment trains in an attempt to get down to a required clean up level. Conversely, RAAS may also find that the required level is so restrictive that no combination of treatment technologies will work. In this situation, RAAS would return a null set. Neither of these outcomes is valuable to the RAAS user.

The following section suggests two methods that RAAS could employ to make best use of available information to generate realistic treatment trains. The first uses sensitivity

¹⁰Future versions of RAAS will be integrated with a risk assessment expert system. Similar to its interaction with ARARs Assist, RAAS will pass the risk assessment program parameters about the site and potential exposure pathways and the program will return to RAAS the adjusted concentrations which the remediation technology must achieve.

analysis to determine the critical concentration of a contaminant that will allow a technology to be used. The second looks at the issue of waivers to ARARs and attempts to integrate the precedents that have been set in previous records of decision into the RAAS recommendations.

B. Decision Rules to Address ARARs

In the preceding section, proper evaluation of ARARs was shown to be a significant obstacle for the RAAS technology screening objective. Without addressing the regulatory acceptability of a treatment technology, RAAS is likely to propose an unrealistic set of technologies of little use to the user. In order to overcome this problem, this section proposes two strategies to use basic information to better represent the process used to select a set of proposed technologies. The first strategy uses sensitivity analysis and the second uses inferences about waivers to ARARs. Together they will allow RAAS to recommend more realistic treatment trains.

Once the RAAS user has stated the general response action preferred and the level of clean up which must be achieved, RAAS is designed to develop a list of potential technologies by relying on its internal databases and the models for technology effectiveness imbedded in the technology modules. As was discussed above, if a treatment train can not meet the clean up criteria, it will not be included as output for the user even if the criteria is only missed by a small amount. In order to better represent the uncertainty in these decisions and to provide a listing of technologies that is as inclusive as possible, a method to determine the sensitivity of the decision is recommended.

Method One. The method involves relaxing the clean up standard until a technology is found to be applicable and then documenting this break point to the user. When a site has a single contaminant, this procedure is straightforward. When the site has multiple contaminants, each contaminant must be evaluated singly with the others held

constant. These potential cleanup levels must then be tracked through the entire treatment train selection process and reported to the user as hypothetical process options.

If an initial review of the potential technologies determines that few (or no) technologies will meet the cleanup standard, the procedure could then be triggered for each technology that is ineffective on a second pass. In order to make the process more efficient, the user could be allowed to disable the procedure or be allowed to specify a percentage failure level that would trigger the procedure (i.e. if the concentration of contaminant that would have allow the technology to be effective is within 5% of the actual concentration then include the alternative in the module output).

This parameter relaxation method assumes that the models for the technologies are accurate. An alternative strategy would be to use sensitivity analysis to alter the parameters in the technology model to better understand why the technology is ineffective. This is the type of procedure that might be used in a final process design to optimize the system. This detailed level of analysis is not appropriate for screening analysis. Most significantly, it would be very difficult to report the results of the analysis so subsequent screening could use it. Furthermore, because some of the technology models are not true mathematical models of the process, the usefulness of the analysis would be questionable.

As an example of the parameter relaxation method, consider a soil and underlying groundwater contaminated with TCE and benzene. Both chemicals have MCLs under the SDWA that are extremely low (about 5 ppb). In addition, traditional pump-and-treat technologies have proven to be ineffective at reaching these low levels of residual pollution in groundwater (Travis, 1990). Risk assessments which include potential groundwater users in exposure pathways have required residual concentrations in the range of 25-100 ppb. So, even if the user specifies a higher concentration value, the conventional treatment schemes are likely to be ineffective.

In order to generate a usefui list of potential technologies that include both innovative and conventional treatment methods, RAAS must include some technologies that

can not reach the required level of clean up (at least as the technology is represented by the mass balance model in the technology module). The parameter relaxation method would determine the soil or groundwater concentration necessary to allow the technologies to be included. Then, from this list of technologies and concentrations, RAAS would suggest those technologies that came the closest to the required level of cleanup. The program could also document the amount that the parameter had to be relaxed. In a case with multiple contaminants, the program could document which chemical was the more recalcitrant contaminant for each technology.

For a treatment train, RAAS could track both the fact that the technology failed to achieve the cleanup level and the contaminant concentration required to enable the technology. Treatment trains which require contaminant concentrations to be relaxed in successive processes in the train would be discarded as too unrealistic. Through this process, potential treatment trains which have only one weak link may be discovered. This would allow emphasis to be placed on increasing the efficiency of a specific technology within a treatment train. The ability to focus attention on a weak link in an otherwise attractive treatment trains is one of the primary advantages of an expert system. This is exactly the type of value that RAAS can bring to the remedy selection process.

Although this method will slow RAAS processing and necessitate that additional data fields be created and tracked, the object-oriented programming method used for RAAS should allow this additional processing with a minimum of additional memory. Until a failure within the range specified by the user is found, fields to track parameter relaxation need not be created. This feature will more accurately model the method an environmental professional would use to select a list of potential treatment technologies.

Method Two. The second method proposed to better model the CERCLA technology screening process uses the ARARs waivers allowed under the law. Waivers would be screened to suggest potential treatments that might otherwise be excluded as

ineffective. To best understand the proposed method, a brief aside on the language in CERCLA which allows waivers is required.

ARARs Waivers under CERCLA. In the 1985 revisions to the NCP, EPA included five reasons for waiving ARARs at a CERCLA site. These waivers were allowed because certain criteria, like SDWA MCLs, are so restrictive that if determined to be ARARs, no remediation technology would be effective. In the reauthorization process, Congress modified the list of waivers and codified them as a part of the SARA. Section 121 (d) (4) of CERCLA now allows a waiver to be granted for the following six reasons:

- 1) The remedial action selected is only part of a total remedial action that will attain such level or standard of control when completed; (Interim Measures Waiver)
- 2) Compliance with such requirement at that facility will result in greater risks to human health and the environment than alternative option; (Greater Risk Waiver)
- 3) Compliance with such requirements is technically impracticable from an engineering perspective; (Technical Impracticability Waiver)
- 4) The remedial action selected will attain a standard of performance that is equivalent to that required under the otherwise applicable standard, requirement, criteria, or limitation through use of another method or approach; (Equivalent Standard of Performance Waiver)
- 5) With respect to a State standard, requirement, criteria, or limitation, the State has not consistently applied the standard, requirement, criteria, or limitation in similar circumstances at other remedial actions within the State; (Inconsistent Application of State Standard Waiver) or
- 6) In the case of a remedial action to be undertaken solely under section 104 using the Fund, selection of a remedial action that attains such level or standard of control will not provide a balance between the need for protection of public health and welfare and the environment at the facility under consideration, and the availability of amounts from the Fund to respond to other sites which present or may present a threat to public health or welfare or the environment, taking into consideration the relative immediacy of such threats. (Fund-Balancing Waiver)

The name in parenthesis is the designation given to the waiver by the EPA for discussion purposes. The designations will be used in further discussions below. The six waivers are discussed at length in the *Federal Register* notices which announced the 1990 revisions to the NCP (EPA, 1990c; EPA, 1989b).

Although EPA has no formal policy on ARARs waivers, they have been observed to be very reluctant to issue them (Clean Sites, 1990). Their reluctance may stem from their concern that the use of waivers will indicate that the remedies selected are not

protective of human health and the environment. In a recent analysis of waivers in Superfund RODs, EPA noted that the technical impracticability waiver may be a method to address groundwater contamination sites where remedies are projected to require over 100 years of operation (EPA, 1991a). In general however, the EPA continues to use waiver sparingly.

The current use of ARARs waivers has received criticism. A report by the Office of Technology Assessment for the Congress state that waivers were not used because the remedies selected were so weak that they were not necessary (OTA, 1985). If the agency excludes requirements from being ARARs because they are not relevant and appropriate at the site, they do not have to consider waivers. This lack of waivers has been cited as evidence that some potential ARARs have been prematurely waived (Clean Sites, 1990). The confusing and often litigious circumstances surrounding ARARs identification will likely continue to limit the use of waivers.

Because waivers have been used infrequently, the waivers that have been written provide an excellent source of information on those ARARs which are clearly unworkable obstacles. For example, some of the most often waived standards are the MCLs for chlorinated solvents (see below). Information about these waivers can be used to relax the screening criteria based on ARARs to ensure that all potential treatment trains are suggested in the output from the RAAS model.

Using ARARs Waivers. The second method proposed to overcome the limitations of screening for regulatory applicability based solely on numerical contaminant concentrations involves incorporating the status of existing ARARs waivers into the screening criteria used by RAAS. In searching for a source of information to examine existing waivers, I discovered that the full text of all of the RODs for Superfund sites are on a database managed by an EPA contractor.¹¹ The database containing the RODs and can be searched

¹¹The database is called the Records of Decision System (RODS) and it contains the full text of Superfund Records of Decision for hazardous waste cleanup sites nationwide.

by key words as well as by 11 basic descriptive fields. I requested a query of the database based on key words related to waivers. The information was provided from the EPA contractor. On the same day, I discussed my data needs with the HQ EPA ARARs Section staff.¹² They informed me that the HQ EPA policy analysis staff had already conducted a study on waivers. They forwarded me a copy of the report (EPA, 1991a).

The EPA policy analysis staff used the ROD database and queried it by several key words related to ARARs waivers. They found that in 618 RODs issued between 1985 and 1990, 41 contained waivers of one or more ARARs. The breakdown of the waivers by type was as follows:

- Interim Measures Waiver - 17 RODs
- Greater Risk Waiver - 4 RODs
- Technical Impracticability Waiver - 18 RODs
- Equivalent Standards Waiver - 1 ROD
- Inconsistent Application of State Standard Waiver - 0 RODs
- Fund-Balancing Waiver - 1 ROD

EPA found that these waivers were divided among four major types of ARARs. The waivers involved:

- Groundwater standards
- Surface water standards
- Hazardous/municipal waste facility standards
- Soil cleanup criteria (radioactively contaminated soil)

Figure 18 shows the breakdown of the 53 specific ARARs waived. The chart shows that both federal and state standards have been waived. For the purpose of expanding the possible alternatives suggested by RAAS, the primary waivers of interest are those for technical impracticability and for interim measures.

¹²Telephone call to Mr. Jim Cliatt, HQ U.S. EPA, 7 January 1992.

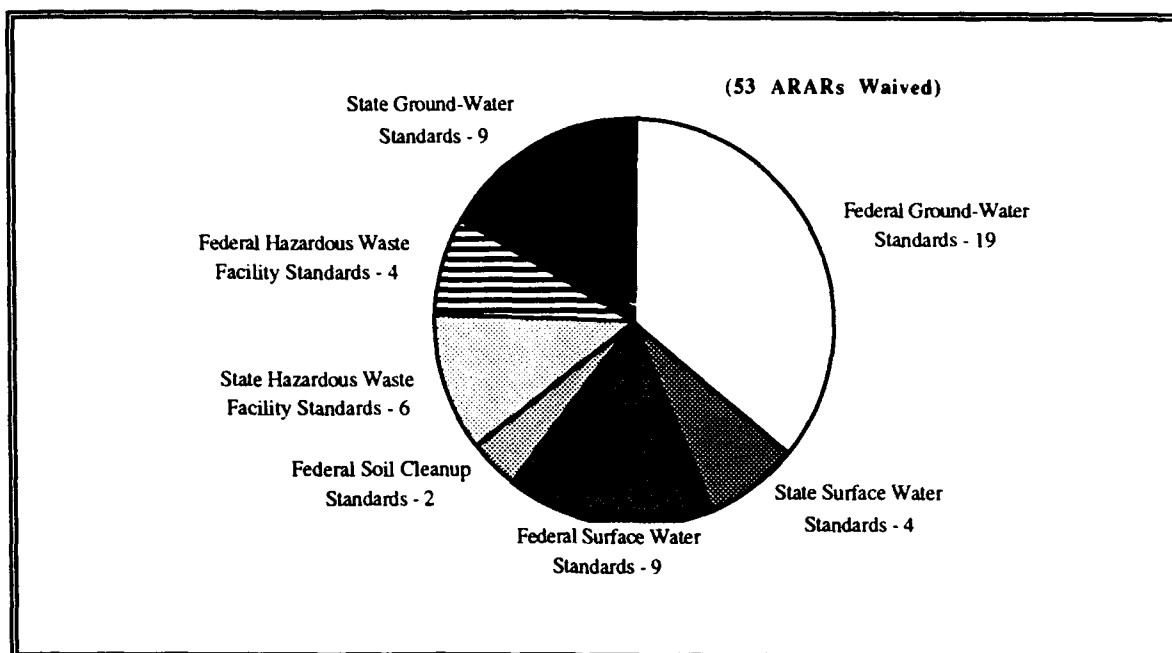


Figure 18. Summary of ARARs Waivers.

Waivers for technical impracticability indicate that the current cleanup technology could not address the contamination problem. If RAAS did not consider these waivers, the program might return the null set or it might return some unrealistic combination of technologies. There is a possibility that one of these unlikely combinations will be an innovative treatment approach, however, it is more likely that technologies will not be implementable as a functional treatment train.

By evaluating interim measures waivers, RAAS can potentially offer a sequenced treatment method. Many RODs currently being written have an interim component that is implemented to mitigate the worst conditions while the more difficult problems are studied further. Under the basic RAAS method, these interim treatments which do not meet ARARs would not be recommended. By properly encoding the types of interim measures used, RAAS can propose a phased approach to better address the contamination at a site.

Using the data developed in the recent EPA waivers analysis, the following section describes the conditions which warrant consideration of waivers for technical impracticability and for interim measures. The information is presented as a set of

if...then... statements which could be encoded into RAAS and integrated into the screening procedures for the development of treatment trains.

C. Decision Rules to Address ARARs Waivers

In order to develop logical statements that can be used to identify circumstances similar to those in which ARARs waivers have been invoked, the detailed description of each waiver-containing ROD was examined. From each description, three key data elements were taken: the contaminant or contaminant type, the contaminated medium and the specific ARAR being waived. For many of the interim waivers, the specific ARAR which was being waived was not identified. Rather, the general type of regulation was identified (e.g. a MCL for groundwater). This level of information is sufficient for this analysis because all three data elements can be taken from the general statements. In addition, the detailed descriptions of the waivers for technical impracticability often did not specify which of the several organic contaminants or metals at a site were the governing contaminant for the waiver. Instead, the report noted that a MCL or FWQC for "volatile organics" or "heavy metals" was waived. Again, for the purposes of identifying situations for screening, the data is adequate.

The results of this analysis are presented in Table 13. The table identifies the contaminant type, medium and standard waived. The table also identifies whether an interim or technical impracticability waiver was used.

Table 13. Analysis of ARARs Waivers.

Contaminant	Medium	Criterion Waived	Type of Waiver
Organics	Groundwater	MCL or State Equiv.	TI/Interim
Organics	Soil	MCL or State Equiv.	TI/Interim
Organics	Fractured Bedrock	MCL or State Equiv.	TI/Interim
Metals	Groundwater	MCL or State Equiv.	TI/Interim
Metals	Soil	MCL or State Equiv.	TI/Interim
Metals/Organics	Surface Water	FWQC or State Equiv.	TI/Interim
PCBs	Soil	State Exposure Guide	TI/Interim
VOCs/Organics	Landfill	Gas Emissions Stds	Interim
Metals	Soils/Groundwater	Air Quality Standards	Interim
Metals/Organics	Ground/Surf Water	State Floodplain Rules	Location Specific
Radium	Soils	Federal Radiation Stds	Interim

As was shown in Figure 17, the most common type of waiver issued was for groundwater standards. These waivers correspond to the first five entries in Table 13. The standards waived in these RODs were federal MCLs or their state equivalent. In several instances, the water standards were the ARARs waived for sites with soil contamination. At those sites, the risk assessment had shown that the soil contamination would foul the groundwater and therefore triggered the drinking water standards as ARARs. The second most common waivers were those for surface water standards like FWQC under the CWA or their state equivalents. The surface water standards were also waived for contaminated soils but were more often waived at mining sites where large quantities of tailings were the source of contaminated runoff.

The remainder of waivers noted in Table 13 were primarily single instances. In the case of the federal soil standards for radioactivity, a large development was built on backfill materials that were contaminated by radium. The federal and state facility standards that were waived were associated with landfills. In three cases, site constraints did not allow the proper slope on the landfill cover to be installed.

Two of the interim waivers were for state air quality standards. These waivers allowed gaseous emissions from a landfill and from a contaminated soils site to exceed RCRA operational facility standards. While these waivers acknowledge that earth moving operations will result in volatilization of contaminants, they also highlight the tenuous link between the RCRA standards applicable at operating facilities and those truly applicable at abandoned Superfund sites. The RCRA standards are often identified as potential action-specific ARARs. For the purpose of technology screening, it is important to note that these types of standards are waived as interim and sometimes final ARARs. Exclusion of a technology based on RCRA standards will unnecessarily shorten the list of potential solutions.

The information in Table 13 can easily be translated into inference rules. For example, statements might read:

If the medium is groundwater and the contaminant is TCE and the standard is the federal SDWA MCL for TCE, then consider a waiver for technical impracticability.

If the medium is soil and the contaminant is arsenic and the standard is the CWA FWQC for arsenic, then consider a waiver for technical impracticability.

This list of statements could be expanded to address each of the circumstances shown in Table 13. Because a total of only 53 waivers have been issued to date, the number of inference rules that would be created from a review of ARARs waivers is small. Of the 53 waivers, only about 30 are directly relevant to technology selection issues. These waivers address some of the more ubiquitous contaminants and should be included so that RAAS can present the user with all of the potentially applicable treatment methods for a site.

By reviewing the documentation for the sites where waivers have been used, one could expand Table 13 to include the exact contaminants and their concentrations allowed in the waiver. This information, and a reference to the ROD in which the waiver was allowed, would give the RAAS user the data needed to justify the use of a technology that will not achieve the proposed ARAR for a site. This method is not intended to avoid standards which are protective of human health but rather to identify those standards which are unrealistic and could result in unnecessarily expensive clean up remedies being specified.

Summary. In this section, the importance of ARARs in the CERCLA remedy selection process has been discussed. ARARs establish the clean up standards for a site. Because the source of ARARs is varied and the opportunity for interpretation exists, the ARARs evaluation process is very difficult to model. From the perspective of technology screening, rigid interpretation of ARARs may unnecessarily exclude potential technologies from consideration.

Two methods to overcome this obstacle to effective technology screening were identified. The first involved the use of sensitivity analysis in the RAAS technology module to identify the level of contaminant concentration which would allow a technology to be used. This information could be valuable in designing an interim remedy to address

the problem contaminant. In addition, potential treatment trains that would have been overlooked because of a stringent ARAR may be presented. The second method involves using data about the waivers that have been issued pursuant to CERCLA section 121 (d) to identify treatment methods that do not meet potential ARARs.

Both of the methods described above will help RAAS to identify as many treatment trains as possible. They will also allow RAAS to more realistically model the process which environmental professionals would use to screen technologies. The goal of any automated decision support system is to emulate the skill and effectiveness of a team of human experts. By using simple, readily available information, RAAS can be made to better serve its intended function.

V. Technology Screening

In section II and III above, we examined RAAS's ability to identify potential remediation technologies and arrange them into treatment trains. As output, the RAAS model delivers a list of all potentially effective technologies. This output may range from a single technology to dozens of potential treatment trains. In order to reach its goal of emulating experts in the area of technology screening, RAAS must both identify potential remediation technologies and screen them according to the regulatory guidelines laid out in the NCP.

In this section, we return to the broader issue of the technology screening process as prescribed by CERCLA. According to the EPA, "the primary focus during screening is on identifying those alternatives that are clearly ineffective or unimplementable or that are clearly inferior to other alternatives being considered in terms of effectiveness, implementability or cost." (EPA, 1988f). Having shown how RAAS can identify technologies, we will discuss how RAAS can model the process of screening potential treatment trains to identify those that meet the screening criteria required in the NCP: effectiveness, implementability and cost.¹³

A. Screening Guidelines

The NCP prescribes a very specific process for identifying and selecting a CERCLA site remedy. For the purposes of this analysis, the process can be seen to have three distinct steps: development and screening of alternatives, detailed analysis of alternatives and remedy selection. This discussion will focus on the first of the three steps.

Figure 19, taken from the EPA guidance on conducting feasibility studies (EPA, 1988e), outlines the process of developing and screening potential technologies. The input to the flow sheet is the site characterization and scoping information from the remedial investigation. This information is analogous to the site and contaminant information that a

¹³ See 40 CFR 400.430. These criteria were specified in the 1986 SARA amendments to CERCLA.

user would prepare prior to using the RAAS model. In the next step, the contaminants, media, and exposure pathways identified in the remedial investigation are synthesized to develop an overall goal for the site cleanup. These goals are often driven by chemical-specific ARARs which are based on health-risk factors. Section 300.430 (e) (2) of the NCP provides a detailed discussion of the issues that must be identified in order to set remedial action goals (EPA, 1990c).

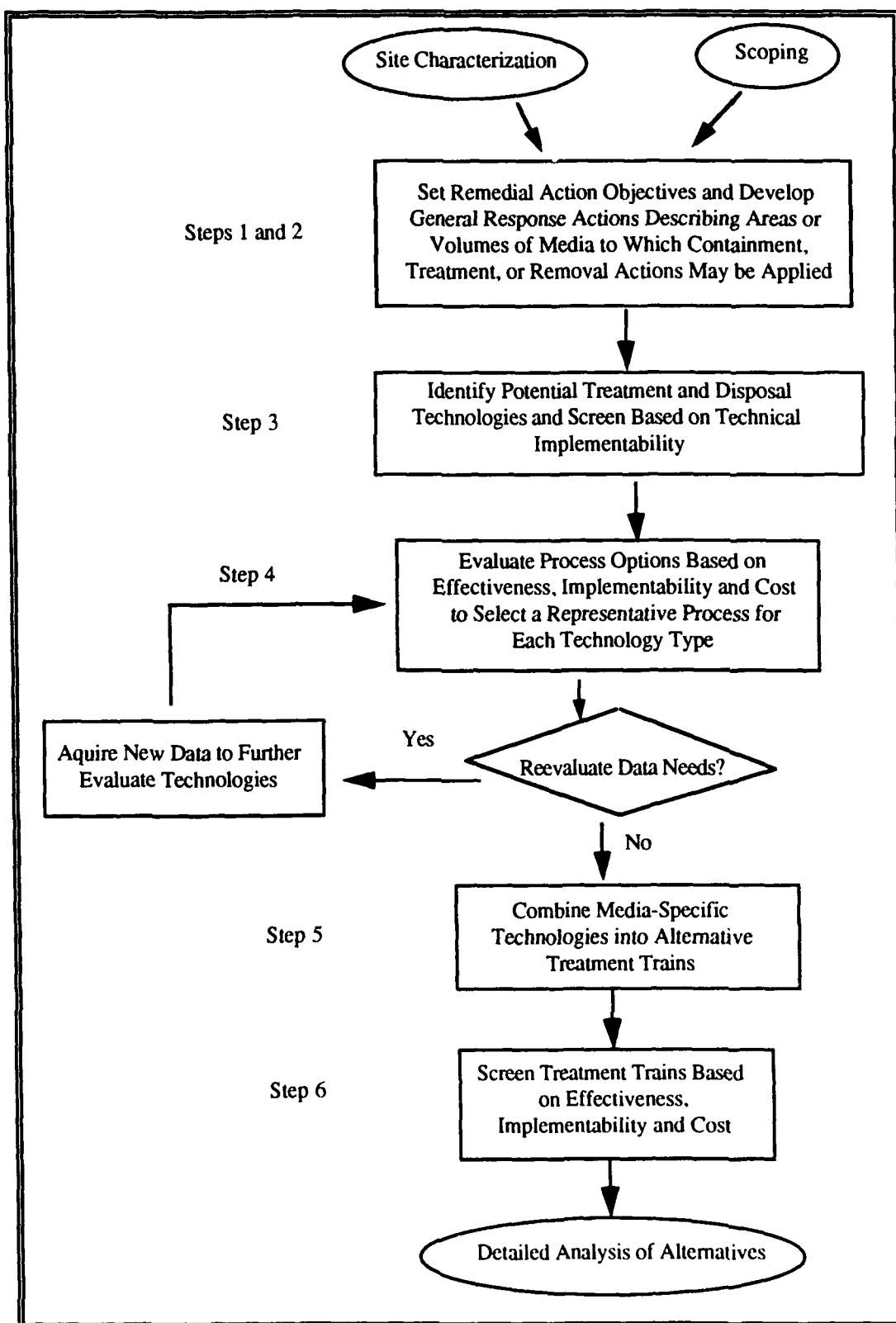


Figure 19. Screening Alternatives--Process Flow Chart.

With this goal established, a general response action (GRA) is identified. As was discussed above, the GRA is simply a basic process model that the remediation might follow. For example, a groundwater contamination site might have a GRA of pump-treat-reinject whereas a sludge lagoon might have a GRA like excavate-solidify/stabilize-dispose. The development of GRAs is one of the first steps required of the user by the RAAS system.

With site and contaminant information and a GRA, RAAS performs the third step in the flow diagram in Figure 19. In previous discussions, we have described RAAS as identifying technologies and arranging them into complete treatment trains in one step. Here we will look at the process RAAS uses to identify individual technologies to meet the requirements for each phase of a GRA. The EPA guidance calls this step selecting all of the potential "technology process options" for a given category of technology (i.e. all of the different incineration processes that would work under the general heading of incineration).

In its current form, RAAS is only capable of performing these first three steps of the technology screening process. The remainder of this section will discuss the improvements necessary in order that RAAS accomplish steps four through six in Figure 18. If RAAS can be enhanced to effectively conduct all six steps, it will achieve its goal of providing the user a list of technologies for further evaluation that have been screened according to the NCP process.

The RAAS technology modules have both applicability criteria and an effectiveness model to determine the technical compatibility of a technology. These technical issues are only one of several criteria outlined in the NCP for identifying applicable technologies in step three of the process. The remaining criteria are regulatory requirements of the law.

In the NCP, EPA has identified four basic regulatory requirements for the alternatives proposed. These requirements include:

- 1) Presenting the no-action alternative;
- 2) Presenting one or more innovative technologies;

- 3) For groundwater contamination, presenting a set of alternatives that achieve the remediation goals in different timeframes; and
- 4) For source control actions, presenting a range of alternatives that include:
 - a) provide protection by controlling exposure to the site through engineering or institutional controls; or
 - b) provide protection by reducing the toxicity, mobility or volume of the contaminant at the site. 40 CFR 430 (e) 3-6.

RAAS may identify technologies that fulfill these requirements but not recognize them as fitting into these categories. In order to accurately represent the full technology screening process identified in the NCP, it must also label the technologies in these categories and ensure that alternatives that meet these criteria are included in the set of treatments that is provided to the user for detailed analysis.

Because these regulatory requirements are somewhat arbitrary, RAAS must be enhanced to capture the definitions of the critical terms and to categorize based upon them. The no-action and institutional control options are straightforward. For each site, RAAS must identify and forward options labeled no-action and institutional controls. Within the area of institutional controls, several options such as fencing or deed restrictions are commonly used. Similarly, if RAAS had all of its technologies labeled as either established or innovative, logic could easily be written that ensured at least some innovative technologies were included. For groundwater, RAAS has the potential to discriminate between technologies based on their required operation times. Different groundwater treatment technologies such as pump and treat or bio-remediation have time components in their effectiveness models. This information could be extracted to ensure that a range of timeframes is identified. Finally, those process options that actually provide treatment of the contaminant, whether through a phase change or chemical transformation, could be identified and labeled.

Having met the regulatory criteria for the types of alternatives that must be forwarded for further evaluation, RAAS must capture the screening methodology indicated as the fourth step in Figure 19. At this point, it might be useful to envision the RAAS output as a list of all potential technologies that meet the basic technical criteria in the technology modules labeled according to the regulatory guidelines identified in the NCP. None of the potential technologies have been eliminated based on any other criteria. The NCP defines three criteria to be used to screen potential technologies: effectiveness, implementability and cost.¹⁴

In order to identify the additional expert knowledge that RAAS must contain so that it can discriminate between technologies based on these three criteria, it is important to understand how the current RAAS technology modules incorporate the definitions of these terms. In Figure 3 above, the nine evaluation criteria used in the detailed analysis of alternatives were shown. The figure also showed how the three criteria for remedy selection prescribed in the NCP related to the nine evaluation criteria. In Figure 20, the three screening criteria are shown in the context of the detailed analysis and remedy selection criteria.

¹⁴The following definitions are used for effectiveness, implementability and cost in EPA guidance.

Effectiveness: Degree to which a technology reduces toxicity, mobility or volume through treatment, minimizes residual risk and affords long-term protection, complies with ARARs, minimizes short term impacts and how quickly it achieves protection.

Implementability: Focuses on the technical feasibility and availability of the technology each alternative would employ and the administrative feasibility of the alternative.

Cost: Cost of construction and any long-term cost to operate and maintain the alternative are considered.

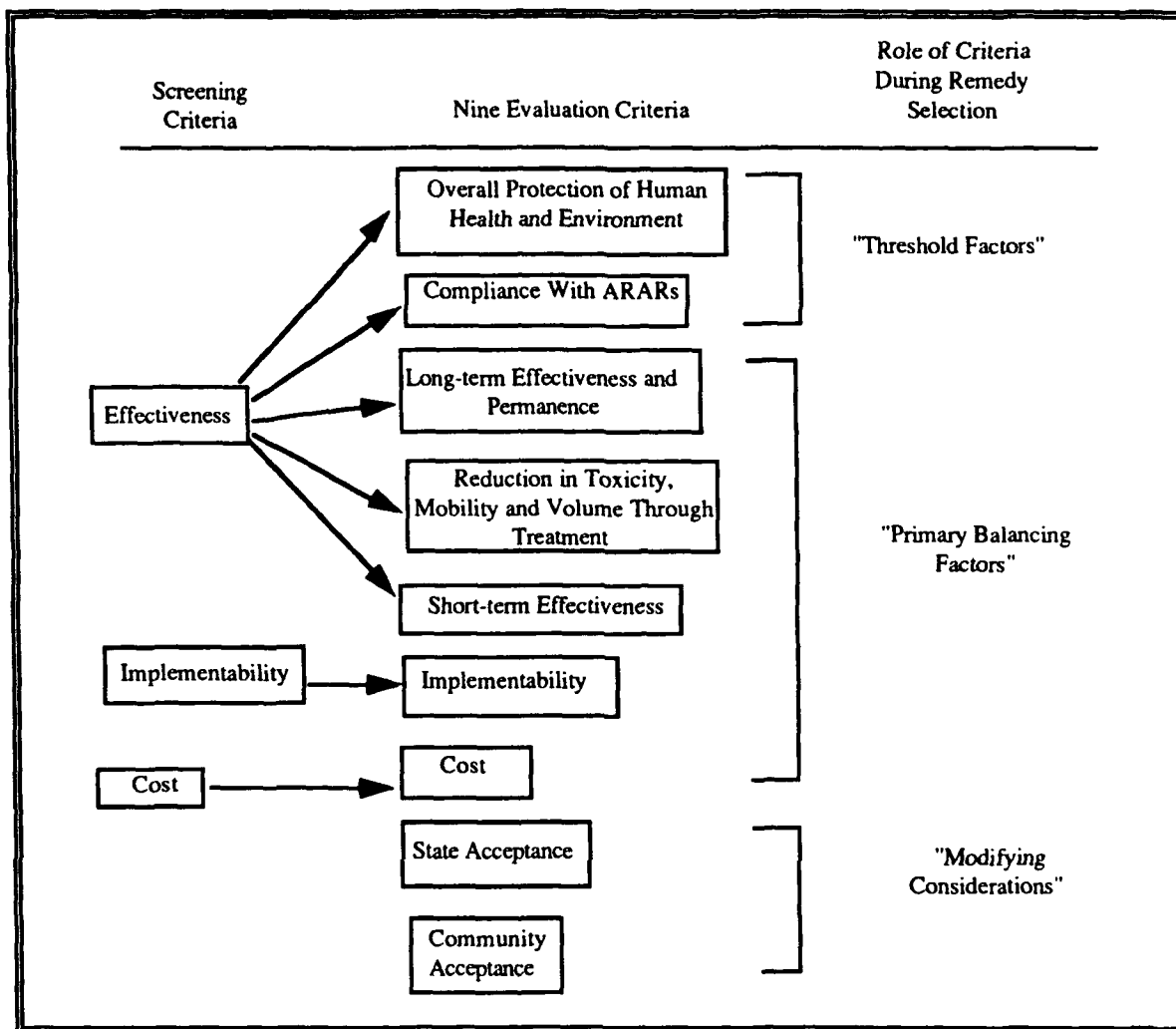


Figure 20. Screening Criteria.

In the area of effectiveness, the RAAS technology modules focus primarily on the issue of reduction in toxicity, mobility and volume through treatment. The output from the effectiveness models could be used to discriminate between technologies. In addition, by providing the basic regulatory criteria as input, RAAS can screen technologies based on compliance with ARARs. The complexities of the ARARs process and its impact on technology screening were discussed in detail in section IV. In its current form, RAAS provides little information about the other aspects of effectiveness.

With respect to implementability, RAAS focuses entirely on technical implementability. In the applicability section of the technology module, RAAS determines if the technology is technically compatible with the contaminant and the medium. As

defined by EPA, implementability also involves other technical site considerations and a host of administrative and logistical constraints that limit implementability. Some of these criteria can be correlated with ARARs issues but others are completely outside the current knowledge base incorporated into RAAS.

Finally, the current version of RAAS does not have the facility to incorporate cost. At the time of this writing, RAAS is being integrated with another decision support system for cost estimating. The cost model being developed by the U.S. Air Force to provide parametric cost estimates for different remedial treatment technology trains. As with the ARARs Assist system described above, RAAS will send parameters to the model and receive in return cost estimates. Although the basis on which the cost estimates are formed and the technical details of the cost estimating process are critical to reliable technology screening, the details of process used by the model are outside the scope of this report. The important issue is that RAAS will have a mechanism to obtain consistent cost information that can be incorporated into the screening process.

In this summary, we have identified two critical areas which must be expanded in order for RAAS to effectively screen technologies in accordance with the guidelines for remedy selection prescribed in the NCP. The RAAS knowledge base must be expanded to include broader definitions of effectiveness and implementability. Furthermore, the RAAS inference rules must be refined so that RAAS can apply this knowledge within the context of the FS process.

Before turning to an analysis of criteria to better define effectiveness and implementability, we will complete our discussion of Figure 19. Using appropriate criteria for effectiveness, implementability, and cost, RAAS can complete step four and then assemble the technologies identified for each GRA into a set of potential treatment trains in step five. As was discussed above, RAAS has the capability to link the individual technologies together into treatment trains. Each technology that effectively accomplishes the specific component of the GRA is linked to a compatible technology that accomplishes

the next step. At this stage, RAAS currently relies on technical criteria to eliminate treatment trains made up of technologies that can not be linked together. Through this process, RAAS can effectively complete step five.

In step six, the last step in the technology screening process, the NCP states that the treatment trains should be screened based on the same three criteria used to identify individual technologies--effectiveness, implementability and cost. It is asserted here that RAAS can utilize the same knowledge base for the three criteria developed for discriminating between individual technologies to discriminate between treatment trains. The key difference is a set of inference rules that apply the knowledge in the context of screening treatment trains. We will discuss the difference between screening technologies and screening treatment trains after establishing the knowledge necessary to represent effectiveness and implementability.

B. Knowledge for Effectiveness and Implementability

In this section, we will explore the process that human experts use to discriminate both technologies and treatment trains based on the criteria of effectiveness and implementability. In the NCP and EPA guidance on performing feasibility studies, the terms effectiveness and implementability are broadly defined. The guidance leaves considerable latitude for the analyst and the decision maker to formulate their criteria and sort the technologies and treatment trains accordingly. From the perspective of developing an expert system to support the process, this variability in definitions introduces the need to handle uncertainty in the model. In addition, the issue of identifying the preferences of the decision maker and ensuring that the model explicitly considers these preferences becomes critical. Without specifically addressing these issues, the model risks the pitfalls of expert systems identified in section II B.

Several methods are available to elicit the information necessary to define effectiveness and implementability. These are the knowledge acquisition techniques

described in section II B above. Three key methods are useful: a review of EPA guidance on the subject, a review of the work of experts implementing the EPA guidance and interviews with experts who perform the work. The EPA guidance can be used to establish the regulatory constraints and set a baseline for the definitions. The work of consulting engineers can then be evaluated to determine the operational definitions actually used in Superfund feasibility studies. Finally, after a set of decision criteria has been mapped from these sources, the definitions can be verified by interviewing both consultants and regulatory decision makers to ensure that they will accept the output of the RAAS model when it uses these definitions.

For this study, the first two methods will be employed. First, the guidance on screening alternatives provided by EPA will be summarized. Then, three RODs from Superfund sites in North Carolina will be examined to determine the criteria for effectiveness and implementability used in the feasibility study. From this information, the common features of the definitions will be outlined. In order to incorporate this information into RAAS, each remediation technology will have to be evaluated based on the definitions. Specific rules for each technology will have to be established. Finally, the program rules which trigger the definitions and document the reasons why technologies are included or excluded will have to be updated to include these screening criteria.

It must be noted that the information presented here is not readily applicable to Superfund sites nationwide. North Carolina falls in EPA Region 4 and all of the FSs reviewed were done under the supervision of Region 4. In addition, the rules will need to be validated by several interested groups. These groups include: EPA and State regulators, engineers, technology vendors, site owners and citizen's groups. Validation is important to ensure that the criteria represent the current knowledge and the current process of screening technologies. The list of potential stakeholders in evaluating the criteria calls attention to the difficulty in automating these subjective definitions. Unfortunately, without validation, the output of the model is certain to be criticized and ignored.

EPA guidance. Two sources of EPA guidance on the screening criteria are available. The process is described in the 1990 NCP and discussed in the preamble to the NCP (EPA, 1988f; EPA, 1990c). EPA further outlines the process in their guidance for conducting RIs and FSs (EPA, 1988e). This guidance has not been updated since the final version of the 1990 NCP was released but the two are consistent.

The definition of effectiveness provided by EPA is best summarized by the links between effectiveness and the first five of the nine criteria for detailed evaluation of alternatives. These links were shown in Figure 20. Compliance with ARARs was discussed in Section IV. EPA notes that protection of human health and the environment is a summary measure of the results of the evaluations of long-term effectiveness and permanence, short-term effectiveness and compliance with ARARs (EPA, 1988d). Reduction of toxicity, mobility and volume can be assessed based on the output of the mass balance effectiveness model incorporated in the RAAS technology module. Thus, for this discussion, the critical elements that must be further defined are long-term effectiveness and permanence and short-term effectiveness.

In their guidance on the detailed analysis of alternatives, EPA provides extensive definitions of long-term effectiveness and permanence and short-term effectiveness. In addition, they suggest analysis factors and a set of specific questions to address the analysis factors for each criteria (EPA, 1988d). Figure 21 shows the analysis factors for long-term effectiveness and permanence and short-term effectiveness developed by EPA. These definitions are also very broad. Attempting to encompass all of these factors into the screening criteria would be very difficult. These broad definitions emphasize the need to look at the work of experts who have implemented these definitions. Human experts will have developed heuristics that capture these bulky definitions in a more manageable form.

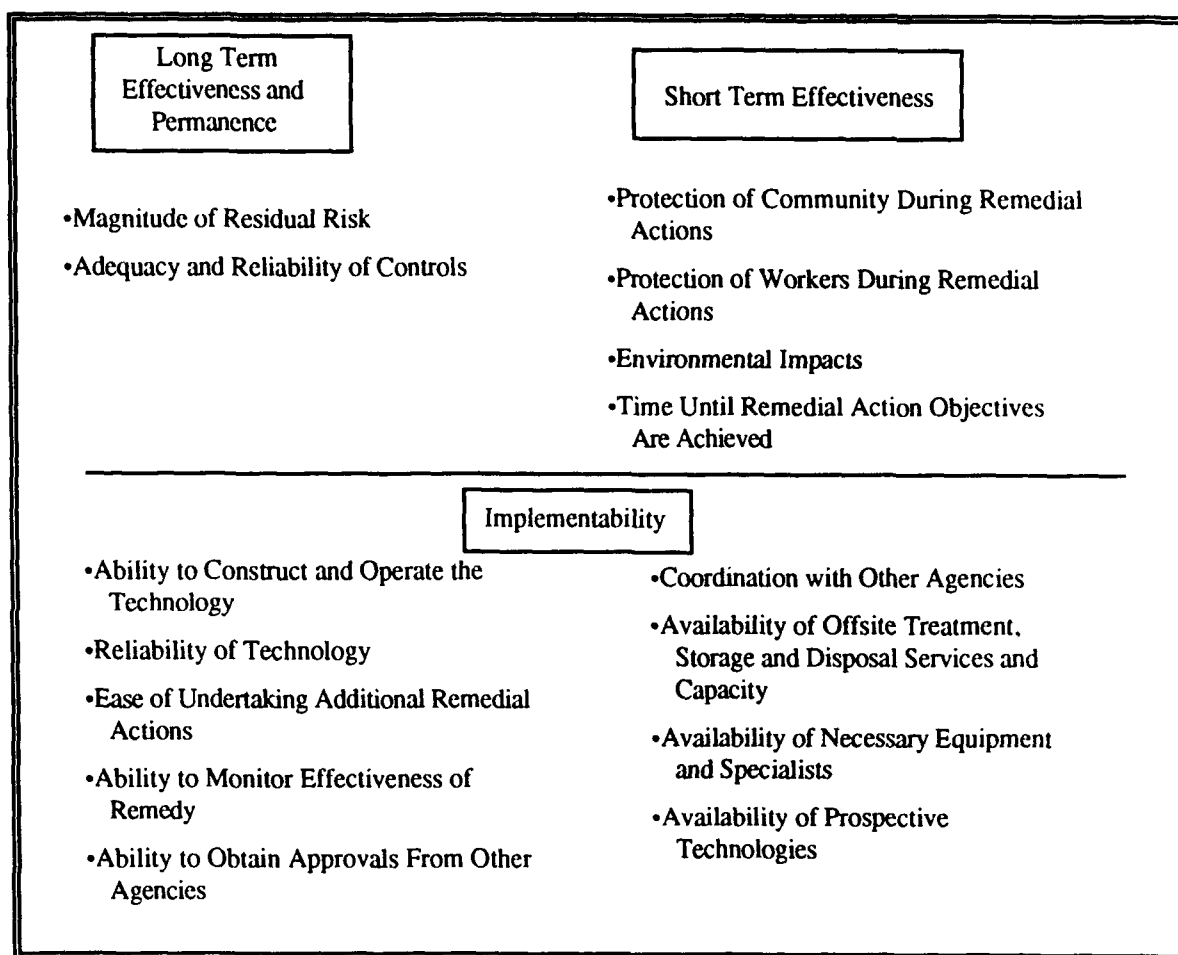


Figure 21. Analysis Factors for Screening Criteria.

The definition of implementability is also best defined by the analysis factors set out by EPA in their guidance on the detailed analysis of alternatives. These factors are shown on the bottom of Figure 21. As with the definition of long-term effectiveness and permanence and short-term effectiveness, EPA's definition of implementability is unworkable. Again, we will turn to the work of experts to better capture this element of the screening criteria.

In the manual process of screening alternatives presented in the EPA guidance, the guidance presents a table to represent the screening step. For each process option for a given remedial technology, short bullet statements on effectiveness, implementability and cost are tabulated. The analyst then identifies the options which are satisfactory. In essence, RAAS must capture this process of tabulating information about each process

option and then select the best among them to represent a given general response action. Similarly, at the stage of screening treatment trains, RAAS must again tabulate information on the screening criteria for each train and then apply heuristics to select viable alternatives to recommend for detailed evaluation. In Appendix D, the type of tables recommended by the EPA guidance are compared to the work of the environmental consultants.

Actual Feasibility Studies. For this report, personnel at the North Carolina Superfund Section, provided access to the feasibility studies conducted for NPL sites located in North Carolina. Three reports were chosen that had been conducted since the latest guidance on screening remedial alternatives was published in 1988.

For each report, the section which discusses the screening of the alternatives was examined to determine the methods that the consultants used to implement the EPA guidance. Not surprisingly, the text of the report refers to the EPA guidance described above. Fortunately, the consultants used simplified definitions of effectiveness and implementability in actually screening the alternatives.

In order to automate the screening process, RAAS must possess testable definitions for effectiveness and implementability. Appendix D compares the three FS reports and examines the definitions used by the consultants. The EPA guidance is used as a reference for the comparison. While no absolute conclusions about the definitions of the screening criteria can be drawn from this simple analysis, the following definitions of effectiveness and implementability are proposed. Each component of the definition can be objectively evaluated. See Appendix D for a detailed discussion.

Effectiveness:

<u>Component</u>	<u>Measure</u>
a. Compliance with Chemical Specific ARARs	Compare output from mass balance model to ARARs provided by user or from an ARARs database.
b. Permanent Reduction of Toxicity, Mobility and/or Volume of Contaminant	Examine percentage removal of contaminant as given by mass balance model.
c. Long-Term Risk	Examine residual risks from contaminant remaining after treatment. Requires link to program that can compute residual risks based on limited information.
d. Short-Term Risk	Examine need for special protective clothing for workers. Requires expanding technology database to include worker protection equipment requirements.
e. Capacity of the Technology	Examine ability of technology to handle quantity of material at the site. Requires parametric scale information in the technology database.

Implementability:

<u>Component</u>	<u>Measure</u>
a. Compatibility of the Technology with Site Constraints.	Include critical site considerations in the technology database. Prompt the user to determine if these disabling site characteristics are present.
b. Compliance with Location and Action-Specific ARARs	Examine the capability of the technology to meet ARARs supplied by an ARARs database or by the system user.
c. Availability of Critical Components	Include need for special materials, equipment, labor or TSD facilities in the knowledge base. Prompt user to see if the components are available.
d. Time Required to Implement	Examine time/quantity curves for the technology. Requires expanding the knowledge base to include parametric time/quantity information.

The multi-component definitions presented here can be qualified/quantified for each technology in the RAAS database. For the ARARs criteria, the definitions rely on the availability of a program that can provide ARARs based on site information. These inputs

could also be overridden by the RAAS user if such a program was unavailable. For the long-term risk criterion, the definition relies on residual risk information from a separate system. For a cursory evaluation, this input data could also be overridden by the user.

Several of the components call for the RAAS database to be expanded to include additional information about the technologies. For example, for the criterion of short-term risk, the database would require information about the need for personnel protective clothing or equipment. If site or contaminant information indicated the need for this additional equipment, the screening routine would report these requirements to the user. The requirement of additional protective equipment would be indicative of a technology with higher short-term risks.

For a criterion like the availability of critical components, the database would have to be augmented with information about critical equipment, materials or personnel skills. When technologies requiring these components were identified, the screening routine would prompt the user to ask if these items would be available. A similar procedure would be used for the site compatibility criterion.

Finally, for the capacity and time criteria, the technology database could be updated to include parametric curves. These parametric curves will show the relationship between the capacity of the technology and effectiveness and will show the relationship between the quantity of material and the time required to implement the technology. The screening module of the RAAS program would provide values from the curves as output to the user.

For the screening module proposed here, the final output would be a table of data which showed the status of each criterion for all screened technologies. The table could be reviewed by the user and the user could then select the technologies that best met the objectives of the general response action.

The definitions proposed here can meet the testability criterion. They are measurable but not arbitrary. By reporting the results to the user in tabular form, the user can see how each criterion was applied. Although they will not work for all potential

situations, they capture the major points of the EPA guidance and are consistent with the work of environmental consultants conducting FSs under current EPA guidance.

By providing the user tabular output and requiring the user to select the best technologies, the screening methodology suggested here does not fully automate the process of screening. This type of methodology is better described as a decision support system rather than an expert system. A decision support system provides the decision maker with a set of tools to more consistently and comprehensively evaluate a set of circumstances prior to making a decision (Newell, 1990)

The process suggested here could be fully automated. By carefully establishing the rating scales for each component of these definitions and coding for the scoring within each technology module, RAAS could fully automate the process option screening step. Several critical issues must be mentioned with respect to full automation. First, the documentation of the process used to reach the final recommendation must be comprehensive. Tabular data would have to be generated by the program which showed exactly why each technology was included or excluded. The fully automated protocol would have to be validated extensively before any regulatory agencies would accept the output. This validation would include both the definitions and the rating scales. In addition, the overall output would require validation. The process of validation is discussed at length in Section VI below.

In summary, the output of the screening methodology proposed here would be the preferred technology for each GRA. The existing RAAS program generates a list of all technologies that are technologically feasible for a site. With the proposed screening method, technologies could be further screened with respect to effectiveness, implementability and cost.¹⁵ The final result is a set of technologies that will work for each general response action proposed by the user for site remediation.

¹⁵The criterion of cost has been excluded from the preceding discussion. It is envisioned that the RAAS program will integrate with a cost model and the screening proposed here could be readily expanded to incorporate the output from the cost model.

The next step in the feasibility study process is to combine the technologies into technology treatment trains that accomplish the complete cleanup required at the site. Automating the screening process for treatment trains is more difficult. While the same definitions of effectiveness and implementability can be used, the information to answer the questions and formulate the scores is imbedded in the relationships between the technologies and the ways in which they are combined. An attempt to use crude representations of these definitions for treatment trains could be very misleading.

The EPA guidance on the selection and screening of alternatives again suggest a tabular approach to the problem. However, in a cursory review of the methods used by consultants to arrange the technologies into treatment trains, it was obvious that the consultants were relying heavily on experience and rules-of-thumb to make their determinations. As we have discussed before, the process of capturing the type expert knowledge used in making these determinations is very difficult. A logical next step in the RAAS development will be to conduct a formal analysis of the EPA guidance and the work of consultants as was done in this report. Because of the varied approaches used and the broad guidance provided by the EPA, a larger sample would be required. A rigorous approach to defining the decision process and collecting the expert knowledge could result in a better model of the process and potentially result in the creation of a decision support system for the decision maker.

We will return to examine the ability to automate the entire remedy selection process in Section VII. In Section VI, we turn to the issue of expert system validation. Validation was mentioned in Section II and again in this section as critical to the acceptance of the expert system. Both a definition of the process of validation and a validation protocol for the current version of RAAS are presented below.

VI. Proposed Validation Method for the RAAS Model

Validation is a critical step for any computer application. Through the validation process, the software is shown to meet the objectives for which it is designed. Because expert systems and decision support systems make decisions or provide critical information on which experts make decisions, validation is especially important. Without adequate validation, decision makers are likely to be very skeptical of the advice provided by the software. Furthermore, because of the reliance on the output of the model, the system developers must be certain that the output is consistent.

The RAAS system requires validation because of its potential for broad usage in the Superfund program. In order for the treatment trains recommended by RAAS to be accepted, several different groups must approve of the method and output of the system. These groups include: federal and state regulatory agencies, site owners, consulting engineers, technology vendors and citizens groups. Without prior validation and agreement to use the output, the benefits of speed and consistency that justify the expense of creating the software will be lost. In fact, if the stakeholders argue over the output of the model, the use of the model may hamper the expedient clean up of a site which threatens public health.

In this section, the critical issues of expert system validation will be discussed. These issues include: the benefits of validation, definitions of key terms and a description of the validation methodology. With these concepts in place, a method to validate the existing phase of RAAS will be presented. Finally, an example of data that could be used to validate RAAS will be presented. The proposed method would compare RAAS output with treatment trains recommended by consulting engineers in previously conducted feasibility studies.

A. Critical Issues in Validation

The time and expense of system validation is warranted because of its benefits. Three groups benefit directly from well planned and executed expert system validation: the system users, the system developers and the domain experts (Gasching, 1983). The end user is the most important beneficiary of system validation. The user gains proof that the system will provide the support that is needed. Users who see a successful product during testing are likely to support future developments. System developers benefit from the feedback. Validation tests allow developers to see how the users view the product and the ways in which they are frustrated by it. The result will likely be a better end product. Finally, domain experts benefit from a systematic validation by seeing how the system represents their knowledge and thought processes. When they see problems, they gain an appreciation for the programming task. This understanding can often facilitate better knowledge acquisition activities in later stages of development. In summary, validation can bring the team together to focus on the program. Through this feedback, the end product can be enhanced.

Terminology. In order to discuss the proper method to evaluate an expert system, it is important to use consistent terminology. For this discussion, validation will mean "the process of determining that an expert system accurately represents an expert's knowledge in a particular problem area." (O'Leary, 1990). As defined, validation focuses on the system and the expert. Evaluation is a broader term. Evaluation is the process of examining an expert system's ability to solve real-world problems in a given problem domain. Under this definition, evaluation assesses an expert system's overall value (O'Keefe, 1987).

Validation has two components: verification and substantiation (O'Leary, 1990). Verification is proof that the model contains the actual problem in its entirety and is sufficiently well structured to permit a credible solution. Substantiation is the demonstration that the model, within its problem area, has an acceptable range of accuracy

consistent with the objectives of the model. Thus, verification focuses on the specification of the model--does the model reflect the real decision process? In contrast, substantiation focuses on accuracy--does the model output match the performance of human experts? To be a useful product, the expert system must produce accurate results and properly represent the process used to get those results.

Validation must not be viewed as an absolute. Validation has different levels which might be attained over the life of the system development. Benfer suggests a hierarchy of validation levels (Benfer, 1991). These levels are summarized in Table 14. Each level of the hierarchy imposes a more stringent test case on the expert system. In the strongest level, the system is tested against cases which are outside the original domain prescribed in the problem definition.

Table 14. Levels of Expert System Validation.

Weakest	Expert finds model acceptable. Consistent with expert's understanding of the problem.
Weak	Expert system preforms accurately for the test cases which were used to design the system.
Strong	Expert system performs accurately for test case from outside the development process.
Strongest	Expert system performs accurately for test cases from an independent universe of samples.

Guidelines for Validation. Extensive energy has been expended on the subject of validating traditional computer software. Early efforts to validate expert systems attempted to use this traditional approach for expert systems. In traditional program validation, each subset of the program is validated and then the main program is sequentially built up and validated (Stunder, 1990). Because expert systems development utilizes rapid prototyping and because each element of the expert system is integrally linked to the others, traditional software validation protocols were found to be inadequate. O'Leary cites technical, environmental, design and domain factors which distinguish expert

systems from other types of computer software (O'Leary, 1987). Thus, a specific set of validation objectives has evolved for expert systems.

Before discussing validation methodologies, it is necessary to identify what expert system components must be validated and when in the development process they should be addressed. Although considerations such as computer hardware, algorithm efficiency, the user interface and cost effectiveness are important issues, the most critical issues for validation are the actual advice or decision created by the system and the reasoning process which the system uses to provide the advice. These two aspects of the program must not be confused. An expert system that gives the right answer for the wrong reasons will not gain the credibility necessary to make it widely useful.

In evaluating the decisions provided by the expert system, careful attention must be given to determine the acceptable range of performance (O'Keefe, 1987). Because expert systems are built to provide information in areas where human advice is subjective and judgmental, it is unrealistic to expect a "right" or "wrong" answer from the system (Gasching, 1983). It is best to establish the acceptable range of performance at the outset of the project and refine it as the system develops. One of the keys to defining the acceptable range of performance is to identify the input domain which the system can be expected to handle. Within this input domain, a set of benchmarks can be established for the system. These benchmarks will provide the boundaries for the range of acceptable performance. Output which fails to meet the benchmarks indicates that the system is not meeting its expectations.

Having focused on the most critical elements for validation, the time in development to evaluate these elements must be determined. Gaschnig suggests a nine-stage progression in the implementation of an expert system. Table 15 summarizes the nine stages. Even with clearly established standards at the outset of development, the system can not be expected to show the same level of competence at all stages. The level of

performance must be coordinated with the stage of development for appropriate and useful validation.

Table 15. Nine States in Expert System Development.

1.	Definition of long-range goals
2.	Implementation of prototype
3.	Refinement of System
	-Informal test cases
	-Revisions based on user feedback
4.	Formal evaluation of performance
5.	Formal evaluation by users
6.	Field test prototype for extended period
7.	Follow-up study on prototype performance
8.	Final revisions to prototype
9.	Release and support of operational program

Both qualitative and quantitative methods for system validation are available. Quantitative methods are most appropriate for validation of systems which produce numerical output or for validation where the model can be compared to a significant number of human experts. Methods to evaluate numerical output include statistical tests such as paired t-tests and confidence intervals. For comparison between the model and multiple experts, a linear model for reliability can be constructed and correlation coefficients calculated (O'Keefe, 1987). Because the RAAS model does not produce numerical output and because few if any Superfund sites have been evaluated by multiple experts, quantitative validation methods are not appropriate. The discussion below will focus on qualitative methods.

Qualitative methods involve a subjective evaluation of the performance of the expert system. These methods can be highly formalized and involve specifying the type of test, the input parameters and the timing of the test. Formal validation is used to avoid biasing the results in hard to identify ways. Formally documented procedures are especially important for expert systems because of the interaction between rules in the logic base. If validation is conducted in an ad hoc fashion, the results of the test will not allow the system developers to pinpoint the source of the error.

Six potential qualitative validation methods are discussed in this section (O'Keefe, 1987). They are presented with reference to the stringency levels as suggesting in Table 14 above. The six techniques are: face validation, predictive validation, the Turing test, field tests, subsystem validation and sensitivity analysis.

In a face validation protocol, a group of system users, system developers and domain experts make a subjective evaluation of the expert system output based on a set of pre-determined test cases. An acceptable performance range is specified and the output is scored accordingly. This testing is weak with respect to Benfer's scale (See Table 14). It relies on test cases that are typically controlled by the system development team.

Predictive validation uses test cases which are take from historical records. In these tests, the system output is compared directly with the work of experts. This type of testing has the advantage that the effectiveness of the original human expert can be judged and then expert system can be compared to see if it would have done better or worse than the human expert. This type of validation is weak to strong because the test cases can be chosen from cases outside those considered by the expert system development team.

In the Turing test, named after one of the original pioneers in artificial intelligence, the work of a human expert and the work of the computer are presented blindly to the judge. An expert system passes the Turing test if the judge can not distinguish between the computer and the human expert. The primary advantage of the Turing test is that it eliminates an bias the judge might have for or against the computer (Gasching, 1983). The cases used in the Turing test can range from those that would classify the validation anywhere from weak to strongest. Clearly, the computer is more likely to pass the Turing test if the test cases are chosen fro those that were used to develop the system. Thus, passing the Turing test with test cases from an independent sample set would be indicative of a higher level of performance.

In a field test, the expert system is placed in the hands of the end user. The users attempt the use the system for its intended purpose and report any difficulties to the system

developers. While this can be a very rigorous test, the types of problems that are reported can often be from users attempting to use the system outside the prescribed input range. Because the situations are created away from the system developers, it can be very difficult for them to recreate the circumstances and actually determine if there is a flaw in the software. When used properly, field trials can subject the expert system to validation at the strongest level.

Subsystem validation is included in this discussion because of its importance for complex systems. In subsystem validation, the component subprograms are run independently and validated according to one of the other procedures. Subsystem validation tends to more easily uncover errors. Unfortunately, evidence that a subsystem is working properly does not ensure that the full system will operate properly. As with other computer systems that combine results, if the accumulated error exceeds the parameters for the full system, the full system is in error. Subsystem validation will be useful for the RAAS system when it is combined with the other expert systems like ARARs Assist and the Air Force cost model. Each system must be validated independently in order to ensure that errors found in the full system can be attributed to the integration of the component parts.

Finally, sensitivity analysis involves systematically varying the input parameters and evaluating the performance of the system. Sensitivity analysis is useful when few test cases are available for the system. By varying the parameters in a very controlled test, the range of outputs of the system can be found. Sensitivity analysis is also powerful when test case are available. By varying key parameters, the user can introduce some measure of variability into a system that does not otherwise account for variation. This feature is especially important for systems like RAAS which under its first version will consider the input data for site contaminants as point estimates rather than as distributed information. Any system which explicitly deals with uncertainty must be evaluated with sensitivity

analysis to determine the impacts of changes in the uncertain information. Proper sensitivity analysis is indicative of validation at the strongest level.

This detailed discussion of validation is presented to focus attention on the critical issues that must be incorporated into a validation of the current version of the RAAS program. As a summary of the preceding discussion, Table 16 presents a list of potential pitfalls that must be avoided in formulating a validation protocol for RAAS (Gasching, 1983). The method of validation described below will account for these critical issues and provide a useful tool for the system developers.

Table 16. Pitfalls in Expert System Validation.

Failure to clarify what is being evaluated.
Failure to clarify for whom the evaluation is intended.
Biasing the results with preselected cases.
Failure to establish the appropriate standard of evaluation.
Generalizations from results obtained in highly constrained tests.
Failure to establish goals for the test.
Inappropriate evaluation technique for the state of development.

B. RAAS Validation Method

Test Method. The validation method described here addresses both verification and substantiation of the RAAS program. Verification consists of a qualitative evaluation of how the first phase of RAAS addresses the problem of technology screening. Verification at this stage focuses primarily on ability of the RAAS technology modules to capture the process of screening technologies based on applicability and effectiveness. Verification of future RAAS functions can only be made as they are added to the system. The majority of this validation will focus on substantiation. In this analysis, the RAAS technology screening function will be evaluated to see if it has a range of accuracy consistent with the goals of the first phase of the program.

The method proposed to substantiate RAAS would compare RAAS output to technology screening done by environmental professionals. For this analysis, a combination of three of the qualitative methods described above will be used. The methods are: face validation, predictive validation and sensitivity analysis.

Face and predictive validation will be combined in an input-output comparison procedure. Carefully extracted information from three previously completed feasibility studies will be input into the RAAS program. Any difficulties in identifying the type of information required by RAAS will be noted. The output from RAAS will consist of a list of potential treatment trains. These trains will be compared to the treatment trains proposed by the environmental consultants who prepared the original feasibility study for the site.

Sensitivity analysis will focus on varying contaminant and medium properties. Key parameters such as soil conductivities and contaminant concentrations will be varied to determine how the RAAS output is effected by the changes. The results of the sensitivity analysis will permit a discussion of RAAS's ability to incorporate heterogeneous site properties into its recommendation of potential treatment trains.

Because this validation is being conducted on a prototype version of the RAAS program, it is essential to ensure that the procedure does not commit any of the pitfalls suggested in Table 16. Four potential pitfalls are discussed briefly here. First, this evaluation is intended for the system development team. The goal of this validation is to provide additional feedback to the system developers on the performance of the program in realistic settings. As a second critical point, at this stage in its development, RAAS does not attempt to differentiate between any of the alternatives that it presents. The version being validated produces a list of all potentially valid treatment trains based solely on technical applicability and effectiveness. Factors like implementability, cost and non-technical aspects of effectiveness are not addressed. The proper comparison at this stage in the validation is the comparison of the RAAS model output to the list of technology treatment trains developed by the consultants strictly on technical merit. Comparison of

RAAS output to lists which have been screened based on cost or implementability would be inappropriate.

For this test method, the third potential pitfall, establishing an appropriate standard for comparison, is the ability of the computer model to capture the majority of the alternatives proposed by the consultant. One should not expect that RAAS will list the exact technologies that the consultants produced. Rather, the relative number and type of treatment trains must be assessed. RAAS may list several treatment trains that the consultant grouped under a single heading. Conversely, the consultant may differentiate between several technologies that RAAS lumps together. An additional measure of the performance of the RAAS system is its ability to generate potential treatment trains not considered by the environmental professional.

Finally, an appropriate set of cases must be used in this validation method to avoid biasing the results. In order to represent a variety of potential sites, each of the cases used should have a different principle contaminant. In addition, each of the feasibility studies used to develop a case should be conducted by a different environmental consultant. Finally, sites which are all within the same general geographical and geological settings should be avoided. Similarly, if these sites all fall within the same EPA region, any special guidance issued by the region will impact the types of technologies screened for the sites. By accounting for these issues in the analysis, a unbiased evaluation can be accomplished.

Input Data. This section presents an example of data that could be used in the validation protocol described above. The data was taken from the administrative record of a Superfund site located in the State of North Carolina. The information was made available by the staff of the North Carolina Superfund section in the N.C. Department of Health, Environment and Natural Resources. At the site, the record of decision documenting the formal remedy selection has been signed. Where the ROD has been signed, all of the remedial investigation and feasibility study reports are final and the data about the site is extensive.

The level of data available after the ROD has been signed is far in excess of the data that would be available in the RI/FS process when RAAS is designed to be used.

Therefore it is important to select data representative of the data that would be available early in the site investigation process. This data selection is important because the input data for the test must simulate the level of data that was available to the environmental consultant at the time that they formulated the list of potential treatment trains. This data can be found by looking back at the remedial investigation report. RAAS is designed to be used during the RI to assist in focusing the data collection efforts toward those data elements that will aid in evaluating the potential of the most likely treatment technologies.

In the section below, the test site will be described briefly. The contaminants, health risk and remedy selected for the site will be included. In addition, the contaminant and medium properties necessary for the validation will be presented in tables. Finally, the technologies screened by the consultants are shown in tables.

Carolina Transformer. The Carolina Transformer site is a former transformer recycling facility located near Fayetteville, NC. The site was used for recycling activities from approximately 1967 to 1982. EPA conducted an emergency removal action at the site in 1984 to remove barrels of PCB contaminated oils and other contaminated debris. After the removal action, PCB contamination exceeding 50 ppm in the soils still existed at the site. Therefore, further remedial action was required to meet the CERCLA standards.

Contaminants. The primary contaminants are various forms of PCBs. In addition, a significant amount of heavy metals like copper and lead were found on the site.

Health Risks. The primary non-carcinogenic health risk identified in the risk assessment done for the site was from the ingestion of metals in groundwater. The primary carcinogenic risk is associated with dermal contact with the PCB contaminated soils. The risk assessment identified exposures for trespassing adults and children as well as off-site residents as being pathways where risks exceeded the EPA guidelines for PCB exposures (BVWST, 1991b).

Selected Remedy. The final remedy for the site involves excavating contaminated soils and treating them with a solvent extract procedure to remove the organic contaminants. The treatment process will also included a precipitation step to remove metals. Clean soils will be returned to the site. For groundwater, extraction and treatment of the waters for removal of organics and metals will be done. Carbon adsorption and a precipitation step will be used on the groundwater.

Table 17. Medium Properties--Carolina Transformer Site

Parameter	Values	Values
Type of medium	Soil	Groundwater
Location of Medium	In-situ	In-situ
Total Volume	15,345 cu. yards	3,000,000 gal.
Volume Fraction of Solid Phase	95%	n/a
Volume Fraction of Immiscible Phase	n/a	n/a
Volume Fraction of Aqueous Phase	5%	100%
Volume Fraction of Gaseous Phase	n/a	n/a

Table 18. Contaminant Properties--Carolina Transformer Site*

Parameter	Soil Contaminants		Groundwater Contaminants	
	PCB	Dioxins	PCB	Benzene
Concentration in Solid Phase	2,100	4.2E-4	n/a	n/a
	mg/kg	mg/kg		
Concentration in Immiscible Phase	n/a	n/a	n/a	n/a
Concentration in Aqueous Phase	n/a	n/a	52 µg/L	80 µg/L
Concentration in Gaseous Phase	n/a	n/a	n/a	n/a

*These data are representative of the total contamination at the site.

Table 19. Initial Process Options Screened--Carolina Transformer Site--Groundwater

General Response Action	Remedial Technology/ Process Option
No Action	No Action
Institutional Controls	Access and Use Restrictions/Deed Restrictions
	Access and Use Restrictions/Permits
Containment	Vertical Barriers/Soil-Bentonite Slurry Wall
	Vertical Barriers/Cement-Bentonite Slurry Wall
Removal	GW Extraction/Wells
	GW Extraction/Drains
Treatment	Solids Dewatering/Gravity Thickening
	Solids Dewatering/Centrifuges
	Solids Dewatering/Belt filter press
	Solids Dewatering/Vacuum Filtration
	Solids Dewatering/Drying Beds
	Solids Dewatering/Sludge Dryers
	Physical Treatment/Coagulation/Filtration
	Physical Treatment/Media Filtration
	Physical Treatment/Sedimentation
	Physical Treatment/Adsorption
	Physical Treatment/Air Stripping
	Physical Treatment/Steam Stripping
	Chemical Treatment/Neutralization
	Chemical Treatment/Precipitation
	Chemical Treatment/Ion Exchange
	Chemical Treatment/Oxidation
	Chemical Treatment/Reduction
	Chemical Treatment/Electrochemical Reduction
	Chemical Treatment/Green Sand
Disposal	Wastewater Discharge/POTW
	Wastewater Discharge/Surface Water
	Wastewater Discharge/Reinjection
	Atmospheric Discharge
	Landfill/RCRA
	Landfill/ Non-RCRA
	Landfill/TSCA

Table 20. Initial Process Options Screened--Carolina Transformer Site--Soils

General Response Action	Remedial Technology/ Process Option
No Action	No Action
Institutional Controls	Access and Use Restrictions/Deed Restrictions
	Access and Use Restrictions/Fences
Containment	Capping/Native Soil
	Capping/Clay
	Capping/Synthetic Membrane
	Capping/Sprayed Asphalt
	Capping/Asphaltic concrete
	Capping/Concrete
	Capping/Multilayer Cap
	Surface Controls/Grading
	Surface Controls/Soil Stabilization
	Surface Controls/Revegetation
	Dust/Vapor Suppression/Water
	Dust/Vapor Suppression/Organic Agents
	Dust/Vapor Suppression/Membranes
Removal	Excavation/Solids
Treatment	Solids Treatment/Oxidation
	Solids Treatment/Chemical Reduction
	Solids Treatment/Water Leaching
	Solids Treatment/Solvent Leaching
	Physical Treatment/Coagulation/Filtration
	Solidification/Pozzolanic Agents
	Chemical Treatment/Organic Dechlorination
	In-Situ Treatment/Oxidation
	In-Situ Treatment/Chemical Reduction
	In-Situ Treatment/Precipitation
	In-Situ Treatment/Bioreclamation
	In-Situ Treatment/Vitrification
	Thermal Treatment/Incineration
	Thermal Treatment/Pyrolysis
	Air Emissions/Particulate Removal
	Air Emissions/Adsorption
	Air Emissions/Thermal Destruction
Disposal	Atmospheric Discharge
	Landfill/RCRA
	Landfill/ Non-RCRA
	Landfill/TSCA

VII. Discussion and Recommendations

In this section, we will turn to an analysis of RAAS. First, a summary of the current status of RAAS will be made. Discussion will then turn to an evaluation of how RAAS is able to meet its stated objectives. Finally, the section will conclude with recommendations for future versions of RAAS, which if implemented, will improve its utility for potential users.

Discussion. The RAAS program is currently in a prototype version. It has not been released for testing or released for application by its community of users. As it is presently configured, RAAS is capable of taking input about site conditions and contaminant concentrations and suggesting a list of technologies which are technically applicable and technically effective for specific general response actions at the site. The program further arranges the potential technologies into treatment trains for the complete remediation of the site. As written, the program simply provides a list of all potential permutations of the technologies in the general response action categories. The screening currently accomplished by RAAS is based strictly on technical characteristics of each remediation technology. No other criteria for effectiveness, implementability or cost are incorporated into the program database.

The goal for the first phase of RAAS was to provide a list of all potentially applicable technologies. To this end, the program achieves its goal with respect to technical criteria. Unfortunately, while the breadth of technical knowledge in the RAAS database is extensive, the knowledge base contains only a narrow band of the entire realm of expert knowledge required to screen remediation technologies.

In the background section above, the primary advantages of an expert system were noted as speed and consistency. Furthermore, a well modeled expert system captures the full scope of the decision process which also contributes to consistent decision making. Finally, by considering all potential options, an expert system can suggest potential

solutions which might otherwise be overlooked. The current version of RAAS provides speed, consistency and "creativity" in the technical screening of remediation technologies. The first phase is, however, of limited utility because it does not include the full range of criteria required to screen technologies.

The amount of time saved by the existing version of RAAS is limited. The system user must still screen the output of the model based on effectiveness, implementability and cost before proceeding to the detailed analysis of the alternatives and finally to remedy selection. Ultimately, the system must address these issues to provide valuable expert advice. As was mentioned above, no screening criteria for effectiveness, implementability or cost are incorporated in the model. Battelle plans to integrate RAAS with the Air Force's RACER cost model to incorporate cost screening.

In Section V, we considered the incorporation of criteria for screening based on effectiveness and implementability. While plausible definitions were suggested for the terms, the report noted that the knowledge base will have to be expanded and the user interface augmented to effectively accomplish this additional level of screening at the individual technology level. Extending the analysis to complete treatment trains was shown to be a major undertaking requiring an aggressive use of decision modeling and knowledge acquisition strategies.

In Section IV, we examined two ways by which the next phase of RAAS could integrate ARARs considerations into the technology screening process. These methods will improve RAAS's performance in the interim until Battelle can link RAAS and EPA's ARARs ASSIST program.

Sections IV and V of this report provide suggestions for the direction of the next phase of RAAS. By addressing ARARs and the implementation of screening based on effectiveness and implementability, the second phase of RAAS can begin to better address the complete process involved in technology screening and to provide the user with output that saves a significant amount of time. With successful validation and acceptance testing,

this method may gain the approval of regulators and site owners such that it presents a genuine value to the community.

Battelle has issued no formal plans for additional improvements to RAAS beyond this second stage of development. They have indicated that the long range goal for RAAS might be to provide an expert system that fully automates the CERCLA remedy selection process. To meet this goal, long term system development could take one of two paths. One path would create a RAAS system which integrates all of the inference mechanism (RAAS, RACER, ARARs ASSIST) in a single comprehensive expert system. This system would strive to recommend the best option for remediation at a site. A second path would create a RAAS system which serves as a facilitator among the various decision support tools. The system would provide CERCLA managers with a comprehensive means to evaluate options for a site.

While the first path is ideal for a true "expert system," it is not realistic for RAAS. In order to achieve this goal, RAAS would need to implement both the nine-part detailed analysis of alternatives and the final remedy selection based on threshold, balancing and modifying criteria (see Figure 19). Given the difficulties suggested for encompassing the knowledge and decision criteria used to screen treatment trains based on effectiveness, implementability and cost, incorporating these additional elements of the CERCLA process into an expert system is beyond the scope of the expert system paradigm.

Were RAAS to contain sufficient knowledge and inference rules to make a final remedy recommendation, the output would never be accepted by the broad community which must endorse a Superfund Record of Decision. The final remedy selection is in the end a political decision as much as it is a technical one. While decision analysts can attempt to capture the preferences in many decision environments, the enormous number of potential settings in which RODs are made and the large number of potentially affected parties makes the odds of a fully automated system being accepted negligible.

Despite the difficulties, the remedy selection process could benefit immeasurably from the use of decision modeling and automation. Instead of focusing the long-range goal of the RAAS tool on making a single recommendation, the program should follow the second path and configure RAAS as a true decision support system. A decision support system is described as a collection of tools and data that are used to solve problems (Newell, 1990).

In fact, the current plans for RAAS are well suited for the decision support system model (Pennock, 1991). RAAS's current plan to interface with several other programs to provide information on cost, ARARs and risk information is an excellent foundation. By serving as a front end to these systems along with providing technology screening capability and a technology database, RAAS could go far to aid in consistent decision making.

Recommendations. In order to achieve this goal, a prototype system that captures the full remedy selection process should be developed using a decision analysis framework. Instead of attempting to quantify the probability statements associated with the different decisions and preferences in the framework however, the model should focus on creating a methodology to lead the user through the process. This methodology must ensure that all of the critical questions are asked and the answers documented along the way.

In essence, RAAS may evolve into a manager for several domain specific expert systems that facilitate the remedy selection process. To meet this goal, each of the component expert systems must be developed and validated as described in this report. In addition, the decision framework in RAAS that calls these specific systems must be developed and validated in a similar fashion. In order for the system to be accepted and used, it must follow a protocol that both meets the regulatory guidelines of the CERCLA program and represents the manner in which environmental consultants and regulators

implement the program in practice. As with other expert systems, the key issues are consistency and documentation.

By focusing on fully documenting the process of alternative screening, detailed analysis and final remedy selection, the system proposed here will promote faster and more consistent remedy selection. The debate that would be required to validate the model of the process would refocus the attention of CERCLA decision makers on the critical issues. In addition, the program output could potentially serve as a great portion of the feasibility study documentation. By standardizing this output, the overall consistency of the reports would be enhanced. A cursory review of several FS reports conducted for this report found them unreadable. Their lack of consistency forces a decision maker to take considerable time to identify the critical issues at the site. Standardized reports would mitigate this problem.

While this discussion does not address the technical details of implementing such a system, it suggests the most important place where decision analysis and decision automation could be brought to bear on the CERCLA process. Site specific information will still be required for every CERCLA site. In addition, the interpretation of terms and guidelines will still be subject to the understanding and skill of the system user. The system could, however, provide the baseline that is lacking in the broad implementation of the CERCLA program. Because the program has grown so large and because so many different players are involved in each decision, consistency is very difficult to achieve. As a matter of course, the scale of the program breeds the kind of repetition and divergence of methods that drives up program costs in the public sector.

At this time, with the program regulations in place and well established, an effort to force consistency will undoubtedly be met with resistance by those who have capitalized on the level of expertise required to conduct CERCLA RI/FS work. In order to sell such a tool as is proposed here, these personnel must be focused on the business of implementing remedies rather than documenting the extent of contamination. The design and

implementation of remedial actions will always require professional services which can not be automated.

While many Superfund sites are now into the remedial action phase, thousands more sites are likely to require RI/FS work. In order to utilize past experience and acknowledge that the process of remedy selection does not protect public health, CERCLA program managers must consider a tool that would both save time in the process of selecting a remedy and engender a consistent approach to the application of technology, ARARs, risk and cost data in the remedy selection.

Considerable energy has been expended in the media and in academia on the time and cost required to reach a remedy selection. Others have proposed streamlined procedures (Clean Sites, 1990). Nevertheless, approaches that require amending the regulatory or legislative framework will take considerable time and certainly be resisted by those who benefit from extensive studies prior to action. Forcing consistency in the application of the existing framework through the use of the RAAS methodology can be both protective of human health and the environment and cost effective. And these are the two basic goals of the Superfund program.

Recommendation Summary. In summary, the following recommendations are made for future work on the Remedial Action Assessment System.

Examine expanding the technology database for each remedial action technology to include the information necessary to screen the technologies on the effectiveness and implementability criteria proposed in Section V.

Pursue methods to explicitly incorporate ARARs criteria in the initial screening of technologies. The methods suggested in Section IV include evaluating the usefulness of ARARs waivers to expand the list of potentially available technologies for a site and using sensitivity analysis to identify the most difficult to handle contaminants. Both of these methods emphasize the need to consider a broad range of technologies in the screening

process and can be effectively implemented in the existing RAAS technology screening protocol.

Utilize a formal validation approach tailored to the expert system methodology for RAAS validation. The approach suggested in Section VI will test the critical components of system and ensure that the output generated will be acceptable to both system users and regulatory officials.

Finally, focus future developments of RAAS toward providing CERCLA decision makers with an integrated support system which provides them with a wealth of automated tools to examine the central issues in remedy selection. An automated decision support system will combine the capabilities of expert systems to provide domain specific advice with the power of computer to provide documentation and consistency in the decision approach used.

VIII. Conclusions

The purpose of this paper has been to explore the efforts underway at Battelle Pacific Northwest Laboratories to develop a software tool to automate the selection of remedies for CERCLA hazardous waste sites. In the preceding sections, the Remedial Action Assessment System (RAAS) was presented. Analysis was directed toward expanding RAAS's usefulness by adding additional technologies to its database (Section III) and by addressing issues like ARARs (Section IV) and screening criteria (Section V) which must be incorporated into the program methodology. A formal protocol for validation of RAAS was developed (Section VI). Finally, recommendations were made for future versions of RAAS (Section VII).

The size, complexity and potential liability of the Superfund program suggests the need for automated decision support tools to assist CERCLA program managers in reaching difficult decisions. This report discussed how decision support systems can offer three key advantages--speed, consistency and documentation. If properly implemented, the RAAS can provide these advantages to the Superfund program.

This report has emphasized the strengths of the RAAS program. It has the most promise as a means of integrating a number of domain-specific decision support tools and providing the decision maker with a comprehensive methodology to automate the RI/FS process prescribed in the National Contingency Plan. In addition, the report has suggested ways to overcome the limitations of the first phase of the program. By including specific criteria to address ARARs and by expanding RAAS's screening capabilities to include criteria for effectiveness and implementability, the program will be better able to assist decision makers in reaching the Record of Decision for a Superfund site.

If future improvements to the RAAS methodology prove successful, CERCLA decision maker can look forward to a more expedient and consistent remedy selection process. This is clearly to the betterment of the nation as scarce resources must be placed toward protecting public health rather than documenting the nature and extent of contamination.

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Appendix A--In-Situ Surfactant Soil Flushing

I. Applicability Section

Applicable Media:

Surfactant soil flushing works on saturated and unsaturated soils.

Contaminant Applicability:

1. Surfactant soil flushing is applicable for organic contaminants in classes 1-10 if the octanol/water partitioning coefficient for the contaminant is greater than 500.
2. Surfactant soil flushing is applicable for inorganic contaminants in classes 11-14 if the water solubility of the contaminant is greater than 0.1 ppm.

The model described below can also be used to described soil flushing with water as the surfactant. If water flushing is used, the constraints should be modified to account for the water solubility of the contaminants.

Disabling Conditions:

1. In-situ surfactant flushing is disabled if the contaminated medium is not in-situ.
2. Surfactant soil flushing is disabled if the hydraulic conductivity of the soil is less than $1.0E-5$ m/s. Below this conductivity, the micelles of surfactant will have difficulty flowing through the contaminated matrix.
3. Surfactant soil flushing is disabled if the water solubility of the contaminant is greater than 2500 ppm. Water based flushing will be effective for highly water soluble contaminants.
4. Surfactant soil flushing is disabled if the contaminant concentration is greater than 5,000 mg/kg of soil. Above this concentration, the soil is heavily saturated and the pore of the matrix are likely to become clogged with the contaminant/surfactant solution making extraction difficult.

II. Effectiveness Section

Effectiveness:

For applicable organic contaminants in classes 1-10:

The amount of a contaminant removed by surfactant soil flushing is estimated from the concentration of contaminant which remains of the soil after N equilibrium contacts with a pore volume of surfactant solution. The number of equilibrium contacts is determined by the number of flushes required to remove the applicable contaminant with the lowest affinity for the surfactant solution.

For applicable inorganic contaminants in classes 11-14:

The amount of a contaminant removed by surfactant soil flushing is estimated from the concentration of contaminant which remains of the soil after N equilibrium contacts with a pore volume of surfactant solution. The number of equilibrium contacts is determined by the number of flushes required to remove the applicable contaminant with the lowest affinity for the surfactant solution. A different set of partitioning coefficients are used to estimate the efficiency of surfactant flushing on inorganic contaminants.

III. Stream Property Calculations for Module Output:

Flow Diagram:

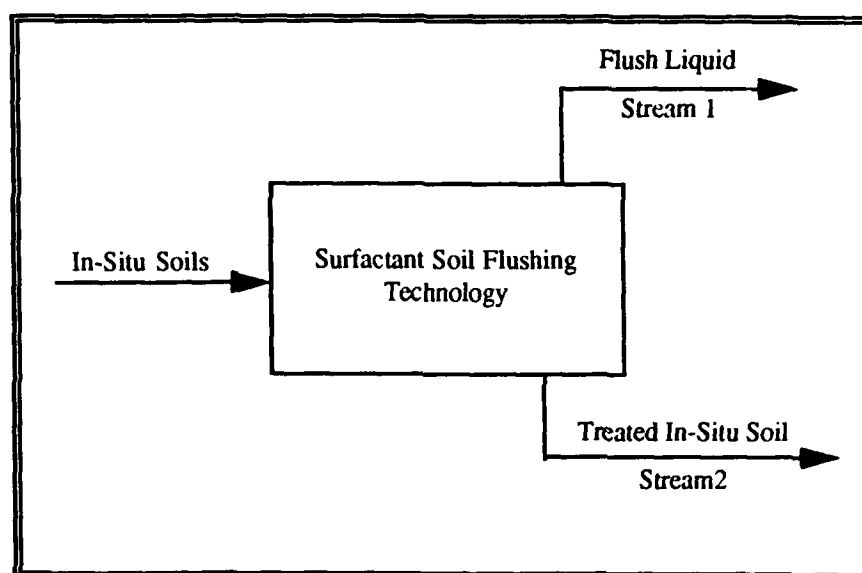


Figure A-1. Flow diagram for the Surfactant Soil Flushing Technology

The surfactant soil flushing module processes in-situ saturated and unsaturated soils. The technology creates two output residual streams: contaminated flushing fluid and treated in-situ soil. The applicability of organic contaminants is based on their octanol water partitioning coefficient whereas the applicability of inorganics is determined based on their water solubility. The model used to represent in-situ surfactant flushing is a mass balance model of a batch flushing system presented by Wilson (Wilson, 1989). It is an accurate first approximation. The concentration of the contaminants in the residual streams and the volume of flushing liquid are determined by estimating the number of equilibrium contacts between the contaminated soil and a pore volume of fluid needed to reduce the concentration of the contaminant to the desired level. Calculations are based on removing the most insoluble contaminants.

The model represents the efficiency of the surfactant by a micelle/water partitioning coefficient K_m . K_m has been shown to be well correlated with K_{ow} (Wilson, 1991, Valsaraj, 1989). The model represents the interaction between the soil and the contaminant by explicitly including an adsorption isotherm. The parameters for surfactant efficiency and soil adsorption can be modified in the model based on the type of contaminant (organic vs inorganic) and can be varied by contaminant as well. Finally, any liquid phase in the original medium is assumed to be displaced by the flush solution and the contaminants in

this phase are found in the flushing liquid. Similarly, contaminants in the gas phase of the original medium are assumed to be removed with the flushing solution.

Nomenclature:

$V =$	Total volume of the medium
$VA =$	Aqueous phase volume fraction of the medium
$VS =$	Solids phase volume fraction of the medium
$VO =$	Immiscible phase volume fraction of the medium
$VG =$	Gas phase volume fraction of the medium
$\rho A =$	Aqueous phase density of the medium
$\rho S =$	Solids phase density of the medium
$\rho O =$	Immiscible phase density of the medium
$\rho G =$	Gas phase density of the medium
$V_{in} =$	Total volume of the original medium
$VA_{in} =$	Aqueous phase volume fraction of the original medium
$VS_{in} =$	Solids phase volume fraction of the original medium
$VO_{in} =$	Immiscible phase volume fraction of the original medium
$VG_{in} =$	Gas phase volume fraction of the original medium
$\rho A_{in} =$	Aqueous phase density of the original medium
$\rho S_{in} =$	Solids phase density of the original medium
$\rho O_{in} =$	Immiscible phase density of the original medium
$\rho G_{in} =$	Gas phase density of the original medium
$CA_i =$	Concentration of the i^{th} contaminant in the aqueous phase
$CS_i =$	Concentration of the i^{th} contaminant in the solids phase
$CO_i =$	Concentration of the i^{th} contaminant in the immiscible phase
$CG_i =$	Concentration of the i^{th} contaminant in the gas phase
$CA_{in,i} =$	Original concentration of the i^{th} contaminant in the aqueous phase
$CS_{in,i} =$	Original concentration of the i^{th} contaminant in the solids phase
$CO_{in,i} =$	Original concentration of the i^{th} contaminant in the immiscible phase
$CG_{in,i} =$	Original concentration of the i^{th} contaminant in the gas phase
$CS_{n,i} =$	Concentration of the i^{th} contaminant on the soil after n equilibrium washes

Stream Properties for Output Stream 1 (Flush Liquid):

The following assumptions were used to determine the properties for stream 1:

- No solid or gas phase exists for this stream.
- Any immiscible phase is removed with the flushing solution and is dissolved in the surfactant solution. This assumes that the liquid contaminant is completely soluble in the surfactant solution.
- The aqueous phase contains all applicable contaminants which are removed from the soil, as well as, any contaminants which were in the gas and aqueous phases of the original medium.
- There is no removal of non-applicable contaminants from the solid phase.

e. Volume changes with mixing are neglected.

1. Location of the medium = Ex-situ
2. Type of medium = aqueous stream
3. Temperature = 293K
4. Pressure = 1 atmosphere
5. pH = 6.0 (final pH will be strictly linked to the surfactant used and the contaminant removed)
6. Volume = Volume of the flushing solution required to remove the least soluble, most strongly adsorbed contaminants. See supporting calculation section below for method to calculate V_{wash} .
7. Volumetric Flow Rate: not applicable
8. Particle Diameter: not applicable
9. Dissolve oxygen concentration: 0.04 kg/m^3 (saturated with oxygen)
10. Total organic carbon (excluding contaminants) = 0.0 kg/m^3
11. Hydraulic Conductivity: not applicable
12. VS = 0.0.
13. VA = V (the total volume of the stream is aqueous)
14. VO = 0.0
15. VG = 0.0
16. $\rho_A = 1000 \text{ kg/m}^3$ (this may need to be modified based on the surfactant used)
17. ρ_S = not applicable
18. ρ_O = not applicable
19. ρ_G = not applicable
20. CA_i (for applicable contaminants in classes 1-14):

$$\frac{V_f[(CS_{in,i} - CS_{n,i})(VS_{in}) + (CO_{in,i})(VO_{in}) + (CA_{in,i})(VA_{in}) + (CG_{in,i})(VG_{in})]}{[V_{in}], V \times VA)}$$

Mass of i which was in the solid, gas, immiscible and aqueous phase of the contaminated soil, less that which is left on the soil after n equilibrium washes

divided by the volume of the aqueous phase of this stream (1.0) See discussion below for method to calculate $CS_{n,i}$.

CA_i (for nonapplicable contaminants in classes 1-14):

$$\frac{[(CA_{in,i}) (VA_{in}) + (CG_{in,i}) (VG_{in})] [V_{in}]}{V_x VA}$$

Mass of i in the original aqueous and gaseous phases divided by the volume of the aqueous phase of this stream.

21. CS_i = not applicable

22. CO_i = not applicable

23. CG_i = not applicable

Stream Properties for Output Stream 2 (Treated Soil):

The following assumptions were used to obtain the properties for stream 2:

- a. No immiscible phase exists.
 - b. Contaminant partitioning to the gas phase can be neglected. This ignore the volatilization of the remaining contaminants.
 - c. There is no removal of nonapplicable contaminants from the solid phase.
1. Location of the medium = In-situ
 2. Type of medium = unchanged from the value specified for the original contaminated medium
 3. Temperature = 293K
 4. Pressure = 1 atmosphere
 5. pH = 6.0 (final pH will be strictly linked water used to flush the surfactant after process is complete)
 6. Volume = volume in
 7. Volumetric Flow Rate: not applicable
 8. Particle Diameter: not applicable
 9. Dissolve oxygen concentration: 0.04 kg/m³ (assumes aqueous phase saturated with oxygen)
 10. Total organic carbon (excluding contaminants) = unchanged from the value specified for the original contaminated medium.
 11. Hydraulic Conductivity: unchanged from the value specified for the original contaminated medium.

12. VS = unchanged from the value specified for the original contaminated medium.
13. $VA = VA_{in} + VO_{in}$ (Assumes any immiscible phase is removed with the flush water and the liquid fraction of the original medium is maintained)
14. $VO = 0.0$
15. $VG = 1.0 - VS - VA$
16. $\rho A = 1000 \text{ kg/m}^3$ (this may need to be modified based on the surfactant used)
17. ρS = unchanged from the value specified for the original contaminated medium.
18. ρO = not applicable
19. ρG = density of air at standard temperature (293K) and pressure (1 ATM).
20. CA_i (for applicable contaminants in classes 1-14):

$$\frac{(CS_{in,i}) (\rho A)}{(\rho S) (K_i)}$$

Where $K_i = 0.63 (K_{ow}) (F_{oc})$. F_{oc} is the fraction of the soil that is organic carbon. The expression is from ***Johnston,1990 and is used to represents the soil water partitioning of organics. It is also a useful approximation for inorganics. It is used here with the understanding that future work will define an appropriate value of K_i for inorganics.

(for nonapplicable contaminants in classes 1-14) = 0.0.

21. CS_i = (for applicable contaminants in classes 1-14):

$$\frac{(CS_{n,i}) (VS_{in}) (V_{in})}{(VS) (V)}$$

Mass of i which remains in the soil after n equilibrium washes divided by the volume of solids in the soil. See the supporting calculations below for a description of how to determine $CS_{n,i}$.

(for nonapplicable contaminants in classes 1-14)

$$\frac{(CS_{in,i}) (VS_{in}) (V_{in})}{(VS) (V)}$$

Mass of i originally in the solids portion of the original contaminated soil divided by the volume of the solids in the soil.

22. CO_i = not applicable

23. CG_i = not applicable

IV. Supporting Calculations

A mass balance on a volume element can be written as:

$$m = m' - v Vc \quad (1)$$

Where

m = mass of contaminant in the material to be treated

m' = mass of the contaminant in material to be treated after flushing

v = voids fraction

V = volume of material to be treated

c = contaminant concentration in surfactant solution after equilibration

The quantity c is defined as:

$$c = [c_o + K_d (C - cmc)] \frac{m'}{m' + m_{1/2}} \quad (2)$$

Where:

c_o = solubility of the contaminant in pure water

C = surfactant concentration

K_d = partitioning coefficient, slope of a plot of contaminant solubility versus surfactant concentration above the cmc

cmc = critical micelle concentration

$m_{1/2}$ = soil- contaminant adsorption parameter, small of adsorption is weak, large if adsorption is strong

The term $\left(\frac{m'}{m' + m_{1/2}} \right)$ is used to account for the reduction in ease of solubilization of the contaminant at low soil contaminant concentrations. At low soil concentrations, contaminants may be strongly bound to the soil by adsorption (Wilson, 1989). The parameter K_d describes the effectiveness of the surfactant. It is equivalent to the micelle-water partitioning coefficient K_m and is also well correlated with K_{ow} (Wilson, 1990; Valasaj, 1989). Wilson used empirical data to develop the following expression.

$$\log_{10} K_m = 1.12 \log_{10} K_{ow} - 0.686 \quad (3)$$

Wilson found a similar expression will several different surfactant-contaminant pairs (Wilson, 1990). The expressions will vary based on the contaminant and the surfactant used. Note that when the surfactant concentration is below the critical micelle concentration ($C < cmc$), the model is applicable for a water based flushing system where partitioning is based on the water solubility, c_o .

If we let,

$$A = vV[c_o + K_d (C - cmc)] \quad (4)$$

and write

$$m = m' + \frac{Am'}{m' + m_{1/2}V} \quad (5)$$

Then we can express m' , the concentration of contaminant after flushing, by the following quadratic equation by rearrangement.

$$m' = \frac{-(m_{1/2} + A - m) + \sqrt{(m_{1/2}V + A - m)^2 + 4 m V m_{1/2}}}{2} \quad (6)$$

This formula can be solved recursively n times to find the mass of contaminant left after n flushings. For the RAAS model, we want to find the number of flushings required so that the concentration of contaminant only changes by 1% per wash. In order to find n , the program must check the calculation $\frac{M_n}{M_o}$ after each iteration of the model. M_n is the mass remaining after the n th flushing and M_o is the mass of contaminant in the soil prior to flushing. When $\frac{M_n}{M_o}$ is less than 0.01, a sufficient number of flushings has been completed.

Based on this discussion, the important calculations are:

$$CS_{n,i} = \frac{m'_i}{(VS)(V)} \quad (7)$$

Where m'_i is the mass of the contaminant remaining on the soil after n equilibrium flushings determined from equation (6) above; and

$$V_{Wash} = n (1 - VS) (V) \quad (8)$$

Where n is the number of equilibrium flushings required to reduce the contaminant concentration so that it does not change by more than 1% per washing. This calculation assumes that the slush solution displaces all voids in the soil matrix and is completely recovered from each flushing operation.

In addition to the calculations noted above, in order to effectively use the model, typical values for several parameters must be developed. These parameters are listed below with their units and typical values.

Table A-1. Critical Parameters for the Surfactant Flushing Model

Parameter	Units	Typical Value
Voids Fraction, v	unitless	0.3
Partitioning Coefficient, K_d	unitless	$0.206 K_{ow}^{1.12}$
Surfactant Concentration, C	g/L	10 g/l
Critical Micelle Concentration, cmc	g/L	1 g/L
Adsorption Parameter, $m_{1/2}$	kg/m ³	1 kg/m ³

The values of K_{ow} and c_o , the water solubility of the contaminant, are found in the RAAS contaminant data base. The values in Table 1 are typical for organic contaminants. Values for typical inorganic contaminants must also be provided. In order to further refine the model, typical values for surfactants for the different classes of contaminants could be programmed into the model. They would be more refined, however, the parameters here should be very useful for a first approximation.

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Appendix B--Solidification/Stabilization

I. Applicability Section

Applicable Media:

Inorganic Solidification/Stabilization:

Inorganic Solidification/Stabilization is applicable for liquids, sludges solids and soils.

Organic Solidification/Stabilization:

Organic Solidification/Stabilization is applicable for dewatered sludges, soils and solids.

Contaminant Applicability:

Inorganic Solidification/Stabilization:

Inorganic Solidification/Stabilization is applicable for contaminants in classes 11 and 14. In addition, arsenic, asbestos and cement dust from contaminant class 13 are applicable.

Organic Solidification/Stabilization:

Organic Solidification/Stabilization is applicable for contaminants in classes 11 and 14. In addition, arsenic, asbestos and cement dust from contaminant class 13 are applicable.

Disabling Conditions:

Inorganic Solidification/Stabilization:

Inorganic Solidification/Stabilization is disabled for the following conditions:

- a. Water table within 5 vertical feet of the final waste location.
- b. Hydraulic conductivity of the soil greater than $1.0E-2$ m/s.
- c. Concentrations of halide salts, sulfur or Calcium chloride greater than 100 ppm.

Organic Solidification/Stabilization:

Organic Solidification/Stabilization:

- a. Water table within 5 vertical feet of the final waste location.
- b. Hydraulic conductivity of the soil greater than $1.0E-2$ m/s.
- c. Concentration of oxidizers greater than 100 ppm.
- d. Concentration of sulphates or halide salts greater than 100 ppm.

Additional Disabling Criteria:

- 1 In-situ Solidification/Stabilization is disabled if the contaminated medium is not in-situ.

II. Effectiveness Section

Effectiveness:

For applicable inorganic contaminants in classes 11 and 14:

The contaminant which is found in the aqueous, immiscible or solid phase of the waste material is permanently solidified and stabilized in the cement matrix. Because of the applicability criteria which eliminate any volatile organics from consideration, the gas phase of the matrix is assumed to be lost and to contain an insignificant level of contaminant.

The process is assumed to be 100% effective for the applicable contaminants.

III. Stream Property Calculations for Module Output:

Flow Diagram:

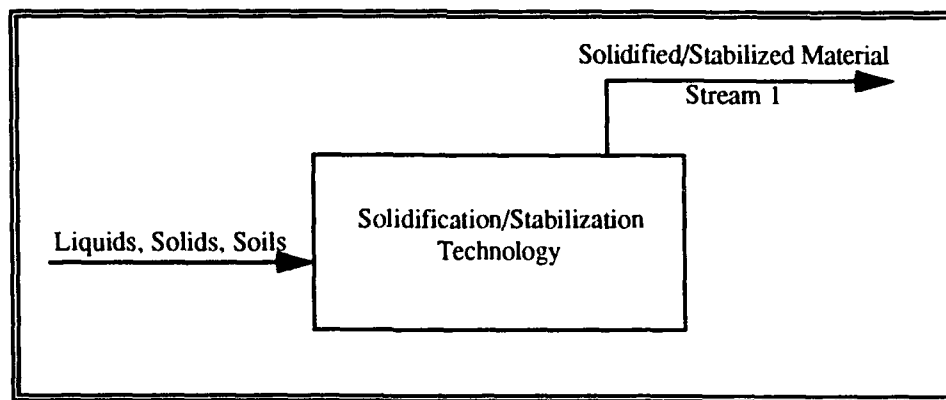


Figure B-1. Flow diagram for the Solidification/Stabilization Technology

The Solidification/Stabilization process used in this module is one which combines a Portland cement binder with the waste matrix. The resultant matrix is a stable solid which can either be monolithic or large chunks of the stabilized matrix. Because Portland cement treatment is the most effective, it will allow S/S to be selected during screening in the largest number of possible situations. The engineer can then evaluate whether another less costly S/S binder could be used in place of the Portland cement.

In a representative Portland cement design, the total amount of cement and other additives might be 30% by weight of the total waste to be treated. This is the amount of binder that will be assumed for all runs of the model.

Nomenclature:

V =	Total volume of the medium
VA =	Aqueous phase volume fraction of the medium
VS =	Solids phase volume fraction of the medium
VO =	Immiscible phase volume fraction of the medium
VG =	Gas phase volume fraction of the medium
ρA =	Aqueous phase density of the medium
ρS =	Solids phase density of the medium
ρO =	Immiscible phase density of the medium
ρG =	Gas phase density of the medium
V _{in} =	Total volume of the original medium
VA _{in} =	Aqueous phase volume fraction of the original medium
VS _{in} =	Solids phase volume fraction of the original medium
VO _{in} =	Immiscible phase volume fraction of the original medium
VG _{in} =	Gas phase volume fraction of the original medium
ρA _{in} =	Aqueous phase density of the original medium
ρS _{in} =	Solids phase density of the original medium
ρO _{in} =	Immiscible phase density of the original medium
ρG _{in} =	Gas phase density of the original medium
CA _i =	Concentration of the i th contaminant in the aqueous phase
CS _i =	Concentration of the i th contaminant in the solids phase
CO _i =	Concentration of the i th contaminant in the immiscible phase
CG _i =	Concentration of the i th contaminant in the gas phase
CA _{in,i} =	Original concentration of the i th contaminant in the aqueous phase
CS _{in,i} =	Original concentration of the i th contaminant in the solids phase
CO _{in,i} =	Original concentration of the i th contaminant in the immiscible phase
CG _{in,i} =	Original concentration of the i th contaminant in the gas phase
V _B =	Volume of the binder material to be used
ρB =	Density of the Binder material to be used.

$$V_B = \frac{[(\rho_S)(VS_{in}) + (\rho_O)(VO_{in}) + (\rho_A)(VA_{in})](V_{in})}{\rho_B}$$

The volume of the binder is the total weight of the material to be treated (the sum of the density times the volume of each phase) divided by the density of the binder material.

Stream Properties for Output Stream 1 (Stabilized Matrix):

The following assumptions were used to determine the properties for stream 1:

- The gas phase of the medium is driven off during the S/S processing
- 30% by weight of Portland cement is used for all S/S processes

- c. No swelling of the final binder/waste matrix occurs. The only volume increase is due to the addition of the binder.
- d. The same quantity of binder is required to S/S a unit volume of any phase of the contaminated matrix

1. Location of the medium = Ex-situ, may be in-situ if so specified
2. Type of medium = solidified matrix
3. Temperature = 293K
4. Pressure = 1 atmosphere
5. pH = 8.0 (final pH will be strictly linked to the Solidification/Stabilization binder used)
6. Volume = The final volume is equal to the Volume of the solid phase of the matrix.

$$VS = [(VS_{in}) + (VO_{in}) + (VA_{in})] (V_{in}) + V_B$$

7. Volumetric Flow Rate: not applicable
8. Particle Diameter: not applicable
9. Dissolve oxygen concentration: 0.04 kg/m³ (saturated with oxygen)
10. Total organic carbon (excluding contaminants) = 0.0kg/m³
11. Hydraulic Conductivity: not applicable
12. $VS = [(VS_{in}) + (VO_{in}) + (VA_{in})] (V_{in}) + V_B$

The volume of the solidified/stabilized mass will be calculated as the sum of the volume of the original soil, aqueous and immiscible phases of the waste plus the volume of the binder added.

13. $VA = 0.0$.
14. $VO = 0.0$
15. $VG = 0.0$
16. $\rho A =$ not applicable

$$17. \rho S = \frac{(\rho S) (VS_{in}) + (\rho O) (VO_{in}) + (\rho A) (VA_{in}) + (\rho B) (V_B)}{VS_{in} + VO_{in} + VA_{in} + V_B}$$

The density of the final mass can be represented as a weight average of the densities of the aqueous, immiscible and solid phases of the waste plus the density of the binder material.

18. ρO = not applicable

19. ρG = not applicable

20. CA_i = not applicable

$$21. CS_i = \frac{[(CS_{in,i})(VS_{in}) + (CO_{in,i})(VO_{in}) + (CA_{in,i})(VA_{in})](V_{in})}{(V_{in}) [(VS_{in}) + (VO_{in}) + (VA_{in})] + V_B}$$

The concentration of the waste in the final matrix can be represented as the sum of the concentration of the waste in the solid, aqueous and immiscible phases divided by the new volume of the material.

22. CO_i = not applicable

23. CG_i = not applicable

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Appendix C--Fluidized Bed Incineration

I. Applicability Section

Applicable Media:

Fluidized bed incineration is applicable for liquids, sludges, soils and solids.

Contaminant Applicability:

Fluidized bed incineration is applicable for organic contaminants in classes 1-10. For contaminants in classes 1-5, the halogen content must be less than 8% by weight of the contaminant mass.

Fluidized bed incineration is not applicable for inorganic contaminants in classes 11-14.

Disabling Conditions:

1. Fluidized bed incineration is disabled if the concentration of alkali metal salts is greater than 5% by weight of the contaminant mass.
2. Fluidized bed incineration is disabled if the particle size is greater than 3 inches in diameter for the dominant fraction of the particles.
3. Fluidized bed incineration is disabled if the trace concentration of metals in contaminant classes 11-14 is greater than 10 ppm.

II. Effectiveness Section

Effectiveness:

For applicable contaminants in classes 1-10, the destruction and removal efficiency for fluidized bed incineration is 99.99%.

For non applicable contaminants in classes 1-14, the destruction and removal efficiency for fluidized bed incineration is 0%.

III. Stream Property Calculations for Module Output:

Flow Diagram:

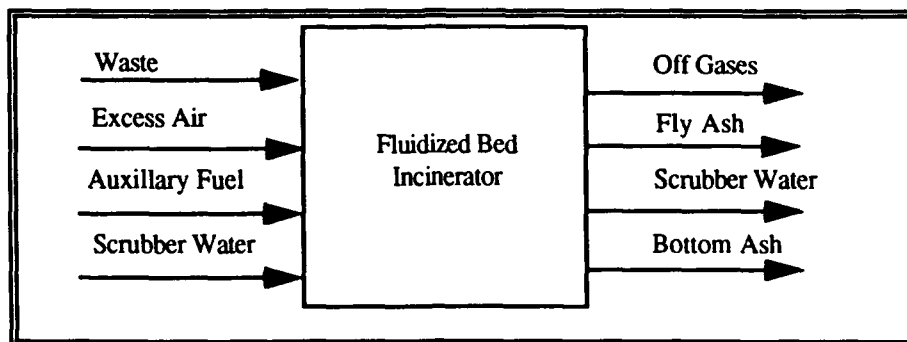


Figure C-1. Flow diagram for the Fluidized Bed Incineration Technology

The schematic assumes that the air pollution control system is a part of the incinerator for the mass balance. There are four input streams for fluidized bed incineration: waste, excess air, scrubber water and auxiliary fuel. The output streams include: off gas, fly ash, scrubber water and bottom ash. Spent bed material can be included with the bottom ash for analysis.

From the perspective of technology screening and development of treatment trains, the off gas can be assumed to meet regulatory standards. Its discharge to the atmosphere will be its final disposal. For ease of calculation, the bottom and fly ash components can also be combined. The resultant mass of ash will require further processing before disposal to ensure that any residual contaminant and trace metals are stabilized. Finally, the scrubber water will entrain ash material and be acidified by the acid gases. It will also require treatment before ultimate disposal.

The fluidized bed incinerator consists of a bed of inert granular material heated to high temperatures and "fluidized" by the introduction of high pressure gases from below the bed material. Figure 14 depicts the fluidized bed incinerator design. One of the primary advantages of the fluidized bed design is that it has no moving parts (McFee, 1985). Heavy materials that settle through the bed and lighter materials that are forced out of the combustion chamber are collected for disposal and the gases are treated with typical incineration pollution control devices.

The primary design advantage of the fluidized bed system is the bed itself. The hot bed material provides excellent mixing and heat transfer conditions. This effective turbulence allows fluidized bed systems to be operated with less excess air and often at lower operating temperatures (Brunner, 1984). Design considerations involve selecting a bed material, typically a sand, that is compatible with the waste and is properly sized for good interparticle contacts. McFee *et. al.* discuss the design of a fluidized bed system specifically for soil combustion.

Because the gaseous emissions are assumed to meet regulatory standards, the final composition of the stream will not be calculated in this model. In addition, because the quantity of scrubber water will be highly variable and the quality of the water will be difficult to determine, it will be assumed to be treated as a part of the pollution control system and discharged in accordance with acceptable NPDES permitting standards. The model described below will focus on the ash fraction of the waste and will combine the fly and bottom ash into one waste stream.

Nomenclature:

V	Total volume of the medium
V_A	Aqueous phase volume fraction of the medium
V_S	Solids phase volume fraction of the medium
V_O	Immiscible phase volume fraction of the medium
V_G	Gas phase volume fraction of the medium
ρ_A	Aqueous phase density of the medium
ρ_S	Solids phase density of the medium
ρ_O	Immiscible phase density of the medium
ρ_G	Gas phase density of the medium
V_{in}	Total volume of the original medium
$V_{A_{in}}$	Aqueous phase volume fraction of the original medium
$V_{S_{in}}$	Solids phase volume fraction of the original medium
$V_{O_{in}}$	Immiscible phase volume fraction of the original medium
$V_{G_{in}}$	Gas phase volume fraction of the original medium
$\rho_{A_{in}}$	Aqueous phase density of the original medium
$\rho_{S_{in}}$	Solids phase density of the original medium
$\rho_{O_{in}}$	Immiscible phase density of the original medium
$\rho_{G_{in}}$	Gas phase density of the original medium
CA_i	Concentration of the i^{th} contaminant in the aqueous phase
CS_i	Concentration of the i^{th} contaminant in the solids phase
CO_i	Concentration of the i^{th} contaminant in the immiscible phase
CG_i	Concentration of the i^{th} contaminant in the gas phase
$CA_{in,i}$	Original concentration of the i^{th} contaminant in the aqueous phase
$CS_{in,i}$	Original concentration of the i^{th} contaminant in the solids phase
$CO_{in,i}$	Original concentration of the i^{th} contaminant in the immiscible phase
$CG_{in,i}$	Original concentration of the i^{th} contaminant in the gas phase
ϵ_i	Destruction efficiency for the i^{th} contaminant
ρ_{Ash}	Density of the ash by-product

Stream Properties for Output Stream 1 (Fly and Bottom Ash):

The following assumptions were used to determine the properties for stream 1:

- Ash fraction of the combusted material is 10%.
- Partitioning of the ash content between bottom ash, fly ash, scrubber water ash and emissions will be 100% to fly and bottom ash.
- Partitioning of the residual contaminant between the flue gas and the ash will be entirely to the ash fraction
- All trace metals will be found in the ash.

- Location of the medium = Ex-situ
- Type of medium = dry solid

3. Temperature = 293K

4. Pressure = 1 atmosphere

5. pH = 6.0

6. Volume =
$$\frac{(0.10) \{ (V_{in}) [(VA_{in}) (\rho A_{in}) + (VO_{in}) (\rho O_{in}) + (VS_{in}) (\rho S_{in})] \}}{\rho A_{sh}}$$

The volume is the ash fraction times the total mass divided by the density of the ash material. The ash fraction is assumed to be 10%.

7. Volumetric Flow Rate: not applicable

8. Particle Diameter: < 3 cm

9. Dissolve oxygen concentration: not applicable

10. Total organic carbon (excluding contaminants) = 0.0.

11. Hydraulic Conductivity: not applicable

12. VS = 1.0

13. VA = 0.0.

14. VO = 0.0

15. VG = 0.0

16. ρA = not applicable

17. ρS = ρA_{sh}

The density of the solid remaining is the density of the ash material. This value is assumed from analysis of previous incineration evaluations done by EPA and is equal to ***.

18. ρO = not applicable

19. ρG = not applicable

20. CA_i = not applicable

21. CS_i

For applicable contaminants:

$$CS_i = \frac{F((1-\epsilon_i) [(CS_{in})(VS_{in}) + (CA_{in})(VS_{An}) + (CO_{in})(VO_{in}) + (CG_{in})(VG_{in})])}{(V_{in}), V}$$

For non applicable contaminants:

$$CS_i = \frac{[(CS_{in})(VS_{in}) + (CA_{in})(VS_{An}) + (CO_{in})(VO_{in}) + (CG_{in})(VG_{in})] (V_{in})}{V}$$

Mass of input contaminant times the destruction efficiency divided by the new volume of material. For the non applicable contaminants the destruction efficiency is assumed to be zero.

22. CO_i = not applicable

23. CG_i = not applicable

IV. References

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Appendix D--Definitions for Screening Criteria

According to EPA guidance, the first step in selecting a final remedy for a Superfund site is to set an overall remediation objective. This objective is then presented as a set of general response actions (GRA) and technologies are identified to accomplish each general response action. Once a set of treatment processes which are technically capable of accomplishing the GRAs is identified, the technologies are then screened based on three additional criteria. These criteria are effectiveness, implementability and cost. Based on the results of this screening, the best technologies for each GRA are arranged into treatment trains that will accomplish the full set of remediation objectives at the contaminated site.

In this appendix, the EPA guidance for screening based on effectiveness and implementability will be compared to the methods used by three environmental consultants in the actual documentation of their feasibility study work. The goal of this comparison is to develop a definition for both effectiveness and implementability that is concise and testable. Concise means made up of three to four comprehensive criteria. Testable means that each of the criteria can be measured based on information readily available during the performance of the feasibility study.

The definitions established here will be used to propose a mechanism in the RAAS program to screen potential technologies on the basis of effectiveness and implementability. By incorporating these definitions into the program, RAAS will be able to more closely approximate the method used by human experts in deriving a list of potential treatment trains for a contaminated Superfund site.

Background

In Figure 19, the definitions of effectiveness and implementability were tied to the criteria prescribed in CERCLA for the detailed analysis of alternatives proposed for a site remedy. It was noted that the essential elements of the definition of effectiveness were the definition of long-term effectiveness and permanence and short term effectiveness. The analysis factors for these essential elements shown in Figure 20 along with the analysis factors identified for implementability. In Chapter 6 of their detailed guidance for conducting RI/FS work, EPA further refined these analysis factors and suggested a set of critical questions for each analysis factor. These detailed questions are shown in Figure D-1. This information is presented to set the baseline for the definitions of these terms.

In their guidance, EPA suggests a graphical method to screen alternatives. Figure D-2 is taken from the EPA guidance. In the figure, one of several possible general response actions for a hypothetical groundwater contamination problem is shown on the left of the page. The remedial technologies and process options identified in columns two and three are screened based on the technical criteria noted in columns four and five. Those options identified as technically feasible are screened for effectiveness, implementability and cost in a chart such as Figure D-3. For each of the technically viable treatment options, the chart presents information about effectiveness, implementability and cost in a bullet format. In their guidance, EPA recommends selecting a set of treatment trains based on this analysis.

In this method of analysis, it is clearly impossible to systematically consider all of the factors suggested in Figure D-1. In order to make the process manageable, consultants have developed heuristics for each of the broad definitions of effectiveness and implementability. By examining four feasibility studies done by environmental consultants, general definitions for effectiveness and implementability will be distilled.

For each of the feasibility studies reviewed, the criteria used by the consultant and an example of their tabular or graphical presentation of the data is given. Following this

information, an analysis of the methods will be presented. For a detailed description of the Superfund sites used in this analysis, see Section VI B of the report.

Data

Carolina Transformer. For the Carolina Transformer site, the consultants followed the EPA guidance very closely. According to their description of their analysis, they used the criteria shown in Figure D-4 for their analysis of effectiveness and implementability. Figures D-5 and D-6 show examples of the the two step graphical approached that they used (BVWST, 1991). The primary difference between the Carolina Transformer study and the EPA guidance is that the consultant combined the criteria for effectiveness and implementability into a single column.

The definitions used by the consultant were very close to those suggested by EPA. The criteria that they used for both terms is highly subjective and difficult to measure. By combining the criteria in their analysis matrix, they present even less information about the criteria in their graphic.

Martin Scrap Recycling Facility. For the Martin Scrap site, the consultants used a narrative evaluation approach. They established a four part definition for both effectiveness and implementability. These definitions are shown in Figure D-7. They called the effectiveness criterion 1 and implementability criteria 1 and 2 high priority criteria. For each process option, they presented a narrative discussion like that in Figure D-8. At the close of each narrative, they made a statement as to whether the technology would be considered further (Ebasco, 1990a).

The definitions used at the Martin Scrap Recycling site are broad and also very subjective. In reviewing the narrative descriptions of the evaluation of each technology, the experts apply the criteria in the definitions in a very qualitative manner. These definitions would also be very difficult to measure objectively.

Jadco-Hughes. For the Jadco-Hughes site, the consultants used a narrative discussion of each option followed by a tabular summary of the analysis. Figure D-9 presents the definitions for effectiveness and implementability detailed by the consultant in their report (CRA, 1990a). As with the other two reports reviewed, the definitions are broad and highly subjective.

Figure D-10 shows an example of the summary table used by the consultant to present the results of the screening analysis. Each of the bullet statements are summaries of the items discussed in the narrative section of the analysis. Figure D-11 shows a summary table from an appendix that the consultant developed for groundwater remediation technologies. In this table, the consultant used an excellent-very good-good-poor rating scheme for effectiveness and implementability. Unfortunately, they note that the scales are subjective and did not provide any clear discussion of the exact criteria that they used to assign the rankings.

Discussion

From the presentation of the data above, it is obvious that the application of the EPA criteria for effectiveness and implementability by consultants who are performing RI/FS work is highly subjective. This subjectivity is inherent in the definitions of the terms. In addition, the way in which consultants have implemented the analysis is quite varied. Both of these issues combine to make the standardization of the approach very difficult.

In order to incorporate this analysis into the RAAS mechanism, the definitions for effectiveness and implementability must be based on measurable quantities that the program can either elicit from the user or determine from the knowledge base stored in the program.

The definitions suggested below attempt to suggest definitions for both effectiveness and implementability that can be taken from existing information. In order to use these definitions in RAAS, the knowledge base in RAAS will need to be expanded. In addition, the program code which implements this screening procedure will need to be able to elicit responses to critical questions from the system user.

Effectiveness. Based on a review of the EPA definitions in Figure D-3 and a review of the work of the consultants presented above, the following five-part definition of effectiveness is proposed:

<u>Component</u>	<u>Measure</u>
a. Compliance with Chemical Specific ARARs	Compare output from mass balance model to ARARs provided by user or from an ARARs database.
b. Permanent Reduction of Toxicity, Mobility and/or Volume of Contaminant	Examine percentage removal of contaminant as given by mass balance model.
c. Long-Term Risk	Examine residual risks from contaminant remaining after treatment. Requires link to program that can compute residual risks based on limited information.
d. Short-Term Risk	Examine need for special protective clothing for workers. Requires expanding technology database to include worker protection equipment requirements.
e. Capacity of the Technology	Examine ability of technology to handle quantity of material at the site. Requires parametric scale information in the technology database.

Of the components listed above, the long-term risk component is most difficult to implement. It requires access to a program that computes risk figures based on basic contaminant and exposure data. Although RAAS will be able to provide contaminant concentrations, a set of realistic exposure scenarios will not be readily available. The use of chemical-specific ARARs information is also dependent on either user input or input from an ARAR's database. Current work by the EPA should make a viable chemical specific ARAR's database available in the near future.

In order to use short-term risk and volume information, the RAAS knowledge base for each technology would need to be expanded to include information pertaining to these issues. For short-term risk, those technologies that require extensive personnel protection could be flagged as requiring protection while the other technologies could be flagged as not requiring protection. For the quantity capacity criterion, each technology database could contain a range of reasonable volumes that could be handled. The program could then compare the site quantities to the range and report the finding to the user.

Implementability. Based on a review of the EPA definitions in Figure D-3 and a review of the work of the consultants presented above, the following four-part definition of implementability is proposed:

<u>Component</u>	<u>Measure</u>
a. Compatibility of the Technology with Site Constraints.	Include critical site considerations in the technology database. Prompt the user to determine if these disabling site characteristics are present.
b. Compliance with Location and Action-Specific ARARs	Examine the capability of the technology to meet ARARs supplied by an ARARs database or by the system user.
c. Availability of Critical Components	Include need for special materials, equipment, labor or TSD facilities in the knowledge base. Prompt user to see if the components are available.
d. Time Required to Implement	Examine time/quantity curves for the technology. Requires expanding the knowledge base to include parametric time/quantity information.

In the definition for implementability, the location/action-specific ARARs data is most difficult to implement. As was discussed in Section IV, the determination of ARARs is very difficult. In order to effectively use this criterion, the program would have to interface with a database of ARARs which was comprehensive. EPA is currently developing a system to address this issue.

For the site characteristic and critical component criteria, the knowledge base for each RAAS technology would need to be expanded to include disabling conditions. The user would then be prompted to determine if these disabling conditions were present at the site. Disabling site conditions might include things like weather or other physical features not commonly considered. For the critical components, the user could be queried to determine if equipment, labor or materials required for the technology are available. In addition, for disposal technologies, the user could be prompted to determine if facilities with adequate capacities and permits are available close to the site.

The definitions proposed would be implemented so that the program generated tabular output showing the status of each component of the definition. The criterion are primarily binary (i.e. yes or no) but others have a range of possible outcomes (e.g. compliance with chemical specific ARARs, time to implement and volume capacities). This tabular data would be presented to the user in a way that highlighted those technologies that met all of the criteria. In addition, for all of the technologies that failed a criterion, the table would document the nature of the failure. From this information, the user could accept or reject the screening done by the computer.

Table 6-1. Long-Term Effectiveness and Permanence

Analysis Factor	Specific Factor Considerations
Magnitude of residual risks	<ul style="list-style-type: none"> What is the magnitude of the remaining risks? What remaining sources of risk can be identified? How much is due to treatment residuals, and how much is due to untreated residual contamination? Will a 5-year review be required?
Adequacy and reliability of controls	<ul style="list-style-type: none"> What is the likelihood that the technologies will meet required process efficiencies or performance specifications? What type and degree of long-term management is required? What are the requirements for long-term monitoring? What operation and maintenance functions must be performed? What difficulties and uncertainties may be associated with long-term operation and maintenance? What is the potential need for replacement of technical components? What is the magnitude of the threats or risks should the remedial action need replacement? What is the degree of confidence that controls can adequately handle potential problems? What are the uncertainties associated with land disposal of residuals and untreated wastes?

Table 6-3. Short-Term Effectiveness

Analysis Factor	Basis for Evaluation During Detailed Analysis
Protection of community during remedial actions	<ul style="list-style-type: none"> What are the risks to the community during remedial actions that must be addressed? How will the risks to the community be addressed and mitigated? What risks remain to the community that cannot be readily controlled?
Protection of workers during remedial actions	<ul style="list-style-type: none"> What are the risks to the workers that must be addressed? What risks remain to the workers that cannot be readily controlled? How will the risks to the workers be addressed and mitigated?
Environmental impacts	<ul style="list-style-type: none"> What environmental impacts are expected with the construction and implementation of the alternative? What are the available mitigation measures to be used and what is their reliability to minimize potential impacts? What are the impacts that cannot be avoided should the alternative be implemented?
Time until remedial response objectives are achieved	<ul style="list-style-type: none"> How long until protection against the threats being addressed by the specific action is achieved? How long until any remaining site threats will be addressed? How long until remedial response objectives are achieved?

Table 6-4. Implementability

Analysis Factor	Specific Factor Considerations
<i>Technical Feasibility</i>	
Ability to construct and operate technology	<ul style="list-style-type: none"> What difficulties may be associated with construction? What uncertainties are related to construction?
Reliability of technology	<ul style="list-style-type: none"> What is the likelihood that technical problems will lead to schedule delays?
Ease of undertaking additional remedial action, if necessary	<ul style="list-style-type: none"> What likely future remedial actions may be anticipated? How difficult would it be to implement the additional remedial actions, if required?
Monitoring considerations	<ul style="list-style-type: none"> Do migration or exposure pathways exist that cannot be monitored adequately? What risks of exposure exist should monitoring be insufficient to detect failure?
<i>Administrative Feasibility</i>	
Coordination with other agencies	<ul style="list-style-type: none"> What steps are required to coordinate with other agencies? What steps are required to set up long-term or future coordination among agencies? Can permits for offsite activities be obtained if required?
<i>Availability of Services and Materials</i>	
Availability of treatment, storage capacity, and disposal services	<ul style="list-style-type: none"> Are adequate treatment, storage capacity, and disposal services available? How much additional capacity is necessary? Does the lack of capacity prevent implementation? What additional provisions are required to ensure the needed additional capacity?
Availability of necessary equipment and specialists	<ul style="list-style-type: none"> Are the necessary equipment and specialists available? What additional equipment and specialists are required? Does the lack of equipment and specialists prevent implementation? What additional provisions are required to ensure the needed equipment and specialists?
Availability of prospective technologies	<ul style="list-style-type: none"> Are technologies under consideration generally available and sufficiently demonstrated for the specific application? Will technologies require further development before they can be applied full scale to the type of waste at the site? When should the technology be available for full scale use? Will more than one vendor be available to provide a competitive bid?

Figure D-1. Analysis Factors for Screening Criteria.

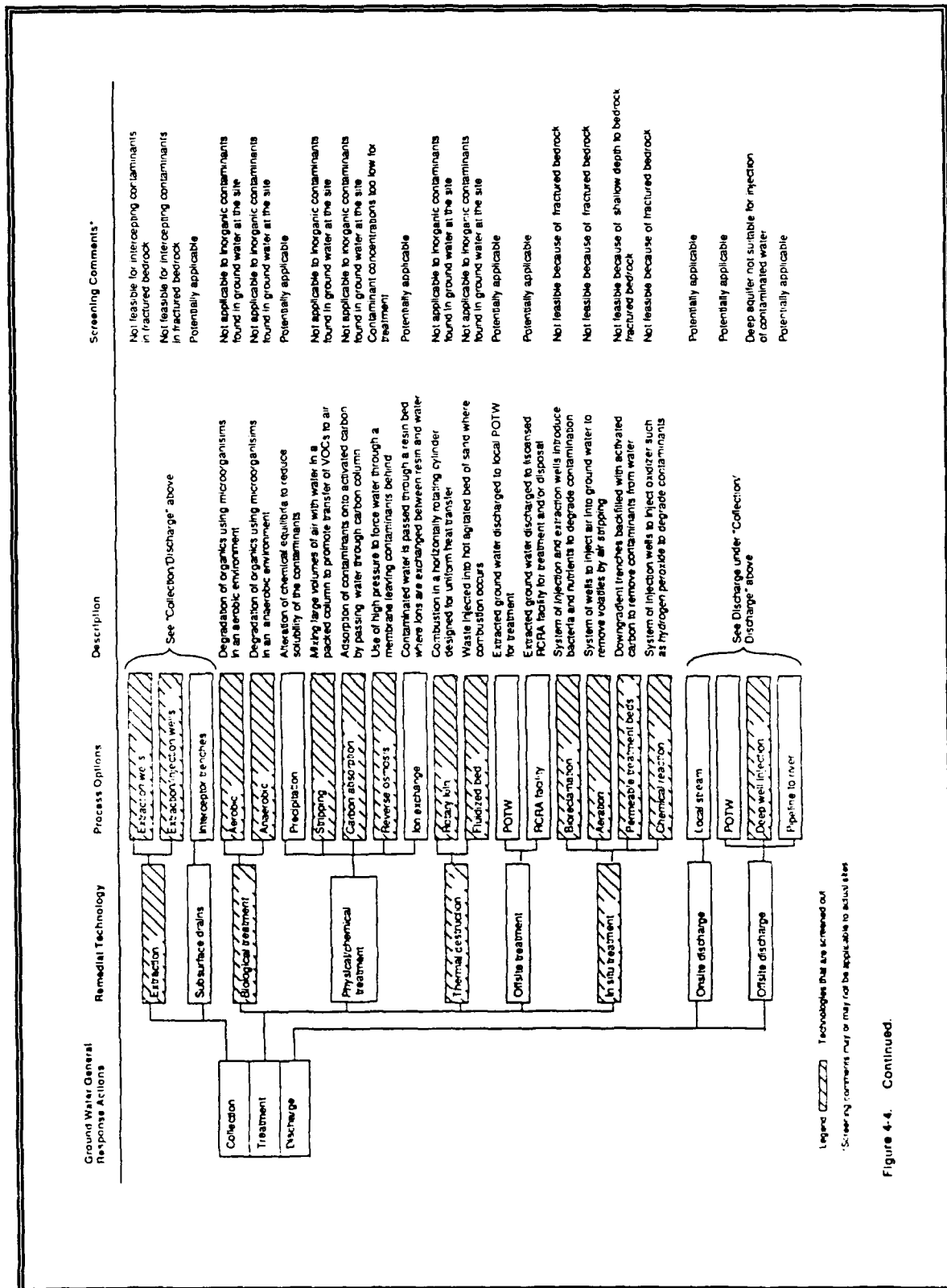


Figure 4-4. Continued.

Figure D-2. EPA Guidance for Screening Based on Technical Criteria.

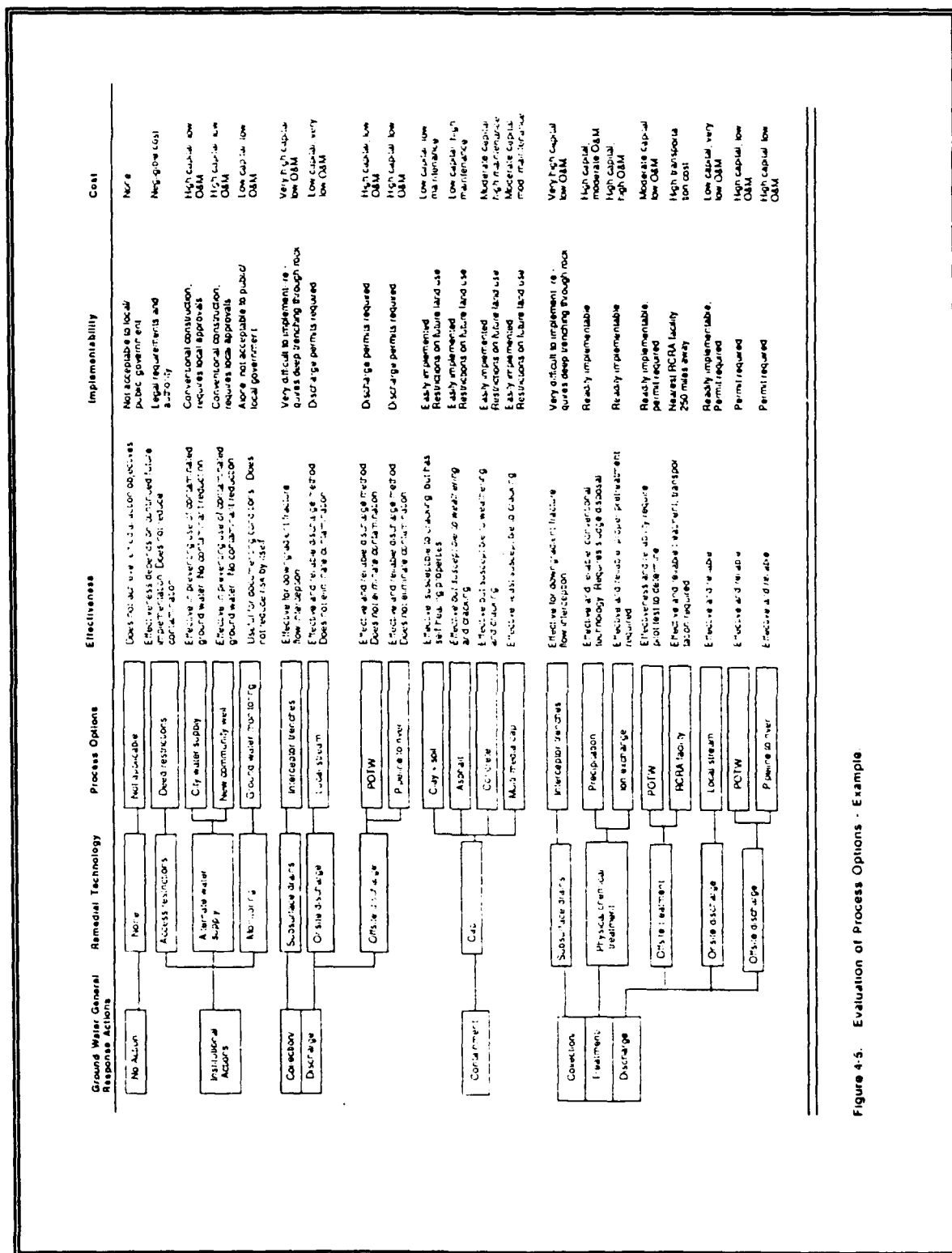


Figure 4-5. Evaluation of Process Options - Example

Figure D-3. EPA Guidance for Screening Based on Effectiveness, Implementability and Cost

Effectiveness:

- The effectiveness of process options to handle the estimated areas or volumes of media and meet the contaminant reduction goals identified in the remedial action objectives.
- The effectiveness of the process option in protecting human health and the environment during the construction phase and operation.
- How proven and reliable the process option is with respect to the contaminants at the site.

Implementability:

- Compliance with location and action-specific ARARs.
- Availability of treatment, storage and disposal services and capacity.
- Availability of necessary equipment and skilled workers to implement the technology.

Figure D-4. Screening Criteria--Carolina Transformer Site.

Table 3-15 Primary Technology Process Option Screening

GENERAL RESPONSE ACTIONS	REMEDIAL TECHNOLOGY	PROCESS OPTION	DESCRIPTION	SCREENING COMMENTS
Removal (continued)	Decontamination	Washing	Contaminated materials are washed with a substance that removes contaminants upon rinsing. Often decontamination is done with a pressurized stream.	Potentially applicable to structures.
		Mechanical Operations	Contamination is removed mechanically by sandblasting or similar means.	Potentially applicable to structures.
	Solids Processing	Magnetic Processes	Magnetic fines separated from non-magnetic solid wastes or debris through the application of a magnetic field.	Not applicable. No magnetic fines.
		Crushing and Grinding	Brittle wastes stressed by impact beyond their elastic limit and broken by heavy, slow moving equipment.	Potentially applicable for structures and debris.
		Shredding and Chopping	Non brittle wastes are reduced to uniform size by mechanically shredding, chopping, crumbling, etc.	Potentially applicable for structures and debris.
		Screening	Solid wastes, including sediments, and debris are separated according to size by screens. Generally performed for coarse material (> 200 microns).	Not applicable.
		Classification	Wastes hydraulically sized using specific gravity differences. Generally performed for fine sized particles (< 200 microns).	Not applicable.
		Neutralization	Acid added to an alkaline waste or base added to an acidic waste to adjust the solids to a pH near neutrality.	Not applicable. No alkaline or acidic wastes.
		Oxidation	Oxidizing agents added to waste for oxidation of organic contaminants to less toxic oxidation states.	Potentially applicable to solid/sediment.
		Chemical Reduction	Reduction agents added to waste to stabilize metals by converting them to a less soluble, more stable form.	Potentially applicable to solid/sediment.

Figure D-5. Technology Screening--Carolina Transformer Site.

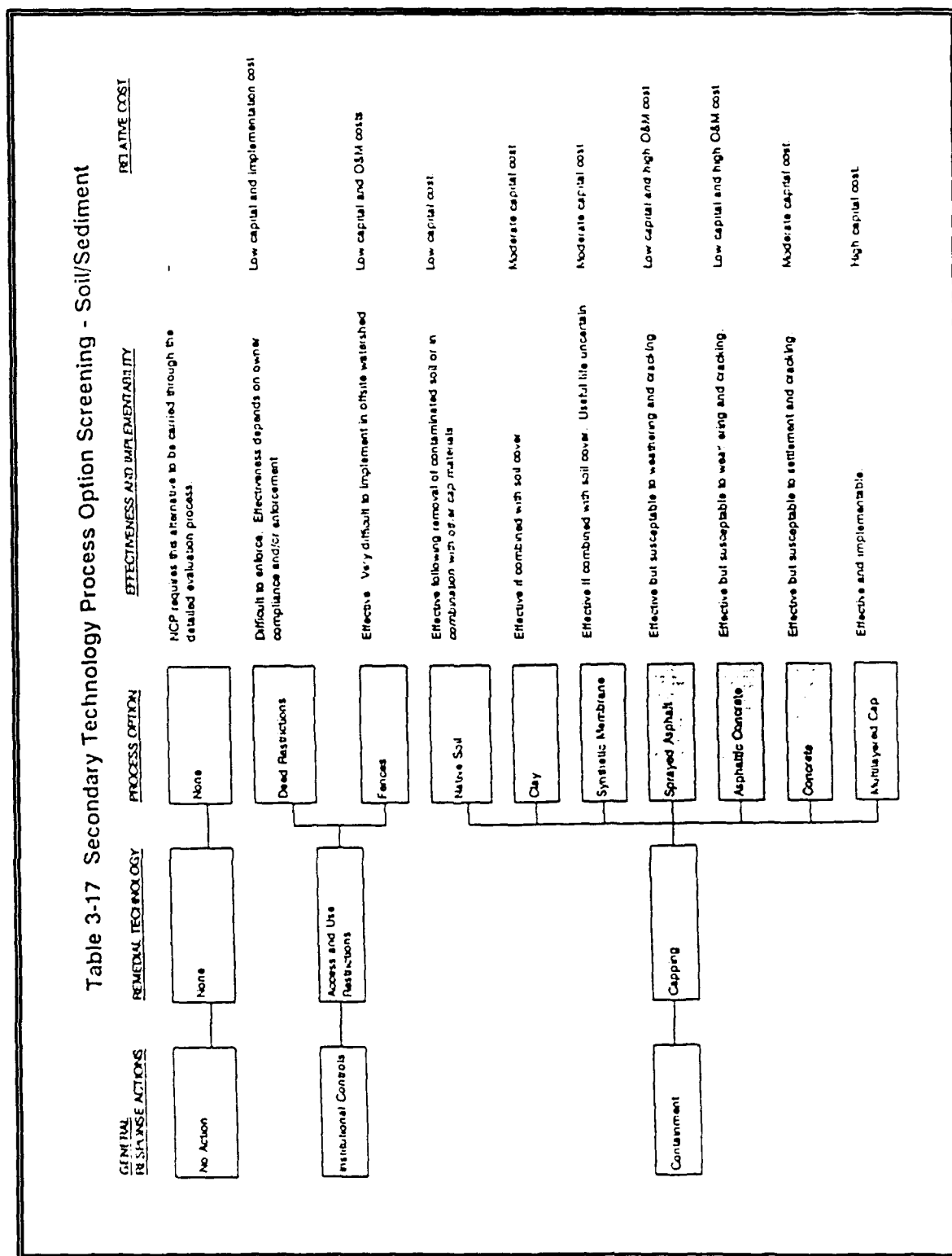


Figure D-6. Screening Based on Effectiveness, Implementability and Cost--Carolina Transformer Site.

Effectiveness:

1. The reliability in meeting chemical specific ARARs or human health based target levels required to achieve response objectives.
2. The degree of permanent reduction in toxicity, mobility or volume achieved by the technology.
3. The long-term risks as a result of treatment residuals or containment system.
4. The risks to the public, workers, or the environment during implementation.

Implementability:

1. The facility characteristics limiting the construction or effective functioning of the technology.
2. Waste or media characteristics that limit the use or effective functioning of the technology.
3. The availability of equipment needed to implement the technology or the capacity of off-site treatment or disposal facilities required to remediate the site.

Figure D-7. Screening Criteria--Martin Scrap Recycling Site.

Soil Washing.

Effectiveness--Reduces volume of contaminated soils; however, produces a large volume of contaminated water requiring treatment. This technology is more effective than in-situ treatment because solid particles are sized and mechanical agitation provides more effective extraction. The mobility is increased due to the nature of the technology.

Implementability--The process requires a high degree of design to match and couple many unit processes to make a feasible system. Bench and Pilot testing is required. Collected wash water is highly toxic or hazardous and requires treatment. The inorganic sludge recovered from treating the wash water requires further treatment and/or disposal. Fine soil particles such as clay and silt are difficult to remove from the washing fluid.

This technology is eliminated because the site-specific conditions limit the effective implementation of this technology. The amount of clays in the soils at the MSR facility limits the effective treatment of the washing fluids.

Figure D-8. Screening Based on Effectiveness, Implementability and Cost--Martin Scrap Recycling Site.

Effectiveness:

Effectiveness is the ability for an alternative to satisfy remedial objectives and contribute substantially to the protection of public health, welfare and the environment. For the Jadco-Hughes site this means alternatives which remediate soil and groundwater contamination. The ability for the alternative to accomplish short and long-term effectiveness and a reduction in toxicity, mobility and volume of contaminants is evaluated. Each alternative is also rated in its ability to meet ARARs.

Implementability:

Implementability is the ability for an alternative to be constructed in a reasonable time frame using accepted technologies. The technical feasibility to construct and reliably operate a remedy is evaluated. Each alternative is also rated as either readily implemented, implemented with moderate concerns addressed or difficult to implement.

Figure D-9. Screening Criteria--Jadco Hughes Site.

TABLE ES-1
SUMMARY OF ALTERNATIVES

Alternative	Effectiveness	Implementability	Cost
4. Cap. Groundwater Extraction, Treatment and Discharge to Fites Creek, Deed/ Access Restrictions, Culvert Replacement and Monitoring	<ul style="list-style-type: none"> eliminates potential on-Site contaminant exposure provision of a groundwater and surface water remedy with contaminant reduction provision of a soil remedy without contaminant reduction by treatment performance of remedy is tracked by monitoring would not achieve remedial objectives 	<ul style="list-style-type: none"> implementable with moderate concern of reliability of groundwater treatment 	CAPITAL: \$1,754,300 ANNUAL: \$233,625 TOTAL PRESENT WORTH: \$5,344,900
5. Soil Vapor Extraction, Soil Flushing, Groundwater Extraction, Treatment and Discharge to Fites Creek, Deed/ Access Restrictions, Culvert Replacement and Monitoring	<ul style="list-style-type: none"> eliminates potential on-Site contaminant exposure provision of a soil, groundwater surface water remedy with contaminant reduction performance of remedy is tracked by monitoring would achieve remedial objectives 	<ul style="list-style-type: none"> implementable with moderate concern of reliability of groundwater treatment 	CAPITAL: \$2,709,300 ANNUAL: \$232,425 TOTAL PRESENT WORTH: \$6,279,900
6. Off-Site Land Disposal, Groundwater Extraction, Treatment and Discharge to Fites Creek, Deed/ Access Restrictions, Culvert Replacement and Monitoring	<ul style="list-style-type: none"> eliminates potential on-Site contaminant exposure provision of groundwater and surface water remedy with contaminant reduction provision of soil remedy without contaminant reduction by treatment performance of remedy is tracked by monitoring would not achieve remedial objectives 	<ul style="list-style-type: none"> difficult to implement due to land disposal restrictions moderate concerns of reliability of groundwater treatment and VOC releases during excavation 	CAPITAL: \$4,235,300 ANNUAL: \$221,125 TOTAL PRESENT WORTH: \$7,632,900

Figure D-10. Screening Based on Effectiveness, Implementability and Cost--Jadco-Hughes Site.

TABLE C.16
COMPARISON OF ALTERNATIVES
JADCO-HUGHES R/FS

<i>Alternative</i>	<i>Effectiveness</i>	<i>Implementability</i>	<i>Cost</i>	<i>Comments</i>
Direct Discharge to POTW	Excellent	Poor	\$353,000	- Belmont POTW requires pretreatment
On-Site Biological Treatment	Excellent	Poor	\$514,000	- flows are too small and process is unsuitable - startup time is too long
Granular Activated Carbon	Good	Excellent	\$4,200,000	- carbon usage is too high - requires pretreatment or additional treatment
Air Stripping	Good	Excellent	\$2,116,000	- does not adequately remove BNAs and inorganics - may be suitable for pretreatment
Ultraviolet Oxidation	Excellent	Very Good	\$2,002,000	- removes most BNAs and VOCs - carried through to Alternatives Screening
Pretreatment by Aeration and Discharge to POTW	Excellent	Excellent	\$1,001,500	- preferred alternative - carried through to Alternatives Screening

Notes:

(1) Implementability and Effectiveness rated on a subjective scale of Excellent, Very Good, Good or Poor.

Figure D-11. Analysis of Alternatives Based on Effectiveness, Implementability and Cost-
-Jadco-Hughes Site..